AGARD-CP-594

AGARD-CP-594

AGARD

ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

7 RUE ANCELLE, 92200 NEUILLY-SUR-SEINE, FRANCE

AGARD CONFERENCE PROCEEDINGS 594

System Design Considerations for Unmanned Tactical Aircraft (UTA)

(les Considérations dans les projects de systèmes pour les aéronefs tactiques et non pilotés)

Papers presented at the Mission Systems Panel 8th Symposium held in Athens, Greece, 7-9 October 1997.

NORTH ATLANTIC TREATY ORGANIZATION

Published July 1998

Distribution and Availability on Back Cover

AGARD-CP-594

AGARD

ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

7 RUE ANCELLE, 92200 NEUILLY-SUR-SEINE, FRANCE

AGARD CONFERENCE PROCEEDINGS 594

System Design Considerations for Unmanned Tactical Aircraft (UTA)

(les Considérations dans les projects de systèmes pour les aéronefs tactiques et non pilotés)

Papers presented at the Mission Systems Panel 8th Symposium held in Athens, Greece, 7-9 October 1997.

North Atlantic Treaty Organization
Organisation du Traité de l'Atlantique Nord

The Mission of AGARD*

According to its Charter, the mission of AGARD is to bring together the leading personalities of the NATO nations in the fields of science and technology relating to aerospace for the following purposes:

— Recommending effective ways for the member nations to use their research and development capabilities for the common benefit of the NATO community;

— Providing scientific and technical advice and assistance to the Military Committee in the field of aerospace research and development (with particular regard to its military application);

— Continuously stimulating advances in the aerospace sciences relevant to strengthening the common defence posture;

— Improving the co-operation among member nations in aerospace research and development;

— Exchange of scientific and technical information;

— Providing assistance to member nations for the purpose of increasing their scientific and technical potential;

— Rendering scientific and technical assistance, as requested, to other NATO bodies and to member nations in connection with research and development problems in the aerospace field.

The highest authority within AGARD is the National Delegates Board consisting of officially appointed senior representatives from each member nation. The mission of AGARD is carried out through the Panels which are composed of experts appointed by the National Delegates, the Consultant and Exchange Programme and the Aerospace Applications Studies Programme. The results of AGARD work are reported to the member nations and the NATO Authorities through the AGARD series of publications of which this is one.

Participation in AGARD activities is by invitation only and is normally limited to citizens of the NATO nations.

* AGARD merged with the Defence Research Group of NATO (DRG) on 1 January 1998 to form the Research and Technology Organization (RTO) of NATO. However, both AGARD and DRG will continue to issue publications under their own names in respect of work performed in 1997.

The content of this publication has been reproduced directly from material supplied by AGARD or the authors.

Printed on recycled paper

Published July 1998

ISBN 92-836-0057-6

Printed by Canada Communication Group Inc.
(A St. Joseph Corporation Company)
45 Sacré-Cœur Blvd., Hull (Québec), Canada K1A 0S7

System Design Considerations for Unmanned Tactical Aircraft (UTA)

(AGARD CP-594)

Executive Summary

The Unmanned Tactical Aircraft (UTA) concept encompasses a broad class of recoverable vehicles designed to conduct the full range of lethal and non-lethal tactical missions.

Technologies are developing rapidly that will enable unmanned aircraft to undertake autonomous and semi-autonomous missions in high threat environments. Unmanned aircraft will operate in conjunction with and sometimes as alternatives to manned aircraft missions. The perceived advantages of utilising unmanned air vehicles are:

- significant reductions in through-life costs
- reductions in losses of aircrew on highly dangerous missions

The main purpose of this symposium was to provide an opportunity for the NATO community to explore and discuss the technological and operational issues associated with the deployment of unmanned tactical aircraft.

The call for papers produced a good response, indicating the importance and timeliness of this subject within the research communities. The symposium was structured into sessions as follows:

- Applications
- Operational Concepts (I & II)
- Advances in UTA Techniques & Technologies (I & II)

The papers presented generated a high level of interest; the symposium was well attended throughout and the programme committee is convinced that the objectives of the symposium were met. Discussions as the symposium proceeded and during the round table session revealed that there was little doubt that there were no technological barriers hindering the deployment of unmanned air vehicles that maintained some degree of operator supervision or control. Fully autonomous vehicles carrying lethal payloads were believed to present greater challenges. Further work is needed in developing operational concepts and addressing policy & doctrinal issues is judged necessary before UTA can undertake a more significant role in future air operations.

Les Considérations dans les projets de systèmes pour les aéronefs tactiques et non pilotés

(AGARD CP-594)

Synthèse

Le concept de l'aéronef tactique sans pilote (UTA) couvre une grande catégorie de véhicules récupérables conçus pour exécuter l'ensemble des missions tactiques létales et non létales.

Des technologies actuellement en évolution rapide permettront aux UAT d'exécuter des missions autonomes et semi-autonomes dans un environnement de forte menace. Les UTA seront exploités parfois avec des avions pilotés et parfois seuls. Les avantages escomptés de l'emploi des véhicules aériens sans pilote sont les suivants :

- diminution sensible des coûts du cycle de vie
- diminution des pertes de vies humaines lors de missions particulièrement dangereuses

Ce symposium a eu pour objectif principal de fournir aux pays membres de l'OTAN l'occasion d'étudier et de discuter des questions technologiques et opérationnelles associées au déploiement des UTA.

L'appel de communications a trouvé un écho très favorable, ce qui témoigne de l'actualité du sujet et son importance pour les chercheurs de l'OTAN. Le symposium a été organisé en trois sessions comme suit :

- applications
- concepts opérationnels (I & II)
- avancées en techniques et technologies UTA (I & II)

Les communications présentées ont suscité beaucoup d'intérêt; l'assistance a été nombreuse tout au long de la conférence, et le comité du programme est convaincu que les objectifs du symposium ont été atteints. Il est apparu très clairement lors des discussions pendant le symposium comme pendant la table ronde qu'il n'existait aucune entrave technologique au déploiement d'UTA, à condition qu'il existe un certain degré de supervision ou de contrôle par un opérateur. Les défis posés par les véhicules totalement autonomes embarquant des charges utiles létales sont plus importants. Des travaux supplémentaires seront nécessaires pour développer des concepts opérationnels et aborder les questions de politique et de doctrine qui se posent. De tels travaux permettraient aux UTA de jouer un rôle plus important dans les futures opérations aériennes.

Contents

† Paper not available at time of printing.

SESSION V: ADVANCES IN UTA TECHNIQUES AND TECHNOLOGIES (SENSORS, PROCESSING DATA FUSION)
Chairman: Dr.-Ing. L. CROVELLA (IT)

Theme

The Unmanned Tactical Aircraft (UTA) concept encompasses a broad class of recoverable vehicles designed to conduct the full range of non-lethal (surveillance, targeting and reconnaissance) and lethal (strike, air-defence and air-to-air combat) tactical missions. The purpose of this symposium is to address the military applications of UTA; the advances in UTA techniques and technologies; and UTA operational concepts.

Interest in unmanned vehicles is increasing rapidly as a result of recent advances in guidance and control as well as other enabling technologies that now provide the basis for a wide range of autonomous or semi-autonomous systems with the potential for operation in high threat environments.

Important operational and technology issues include command and control (e.g. multi-ship flight management), communications, sensors, data processing hardware and software and artificial intelligence and internetting UTA with manned air vehicle operations.

The use of UTA in the next century could involve the utilisation during peacetime of civil air routes subject to civil aviation authorities and ATC regulations and drives the need for redefinition of navigation and guidance rules to address air-space sharing with manned platforms.

The symposium will examine the types of lethal and non-lethal applications and review issues that have been raised in current systems. Military usage and operational considerations will be discussed. Advances in enabling technologies will be covered and cost-effectiveness issues explored.

SESSIONS

I UTA Applications
II Operational Concepts I
III Operational Concepts II
IV Advances in UTA Techniques and Technologies
- Navigation, guidance & control
- Communications & C^3I

V Advances in UTA Techniques and Technologies
- On-board and off-board sensors
- Sensor data fusion & signal processing
- Flight avionics

VI Round Table

Thème

Le concept de l'avion tactique non-piloté (UTA) couvre un large catégorie de véhicules récupérables conçus pour l'exécution de la gamme complète des missions tactiques létales (frappe, défense aérienne et combat air-air) et non-létales (surveillance, désignation d'objectifs et reconnaissance). Ce symposium a pour objectif d'examiner les applications militaires des UTA; les avancées dans les techniques et technologies UTA; ainsi que les concepts opérationnels des UTA.

Les véhicules non-pilotés suscitent de plus en plus d'intérêt en raison des percées récentes réalisées dans le domaine du guidage et pilotage, ainsi que pour d'autres technologies permettant de fournir désormais la base d'un grand éventail de systèmes autonomes ou semi-autonomes capables d'évoluer en environnement à haut risque.

Parmi les questions opérationnelles et technologiques importantes figurent, le commandement et contrôle, (par exemple la gestion du pilotage multi-véhicule) les télécommunications, les senseurs, le matériel et le logiciel informatique, l'intelligence artificielle et l'insertion des UTA dans les opérations pilotées.

La mise en œuvre des UTA au siècle prochain pourrait conduire à l'utilisation, en temps de paix, de voies aériennes civiles régies par les autorités de l'aviation civile et assujetties aux règlements du contrôle de la circulation aérienne. Cette mise en œuvre nécessite la redéfinition des règles de navigation et de guidage afin de permettre d'aborder le problème du partage de l'espace aérien avec les plates-formes pilotées.

Ce symposium examinera les différents types d'applications létales et non-létales et étudiera les questions qui ont été soulevées concernant les systèmes actuels. Les utilisations militaires et les considérations opérationnelles seront discutés. Les avancées en technologies permettant le concept et les aspects coût-efficacité seront examinés.

SESSIONS

I les applications des UTA
II les concepts opérationnels I
III les concepts opérationnels II
IV les avancées en techniques et technologies UTA
- navigation, guidage et pilotage
- télécommunications et C^3I

V les avancées en techniques et technologies UTA
- les senseurs embarqués et non-embarqués
- la fusion des données senseurs et le traitement du signal
- l'avionique de pilotage

VI table ronde

Mission Systems Panel

CHAIRMAN
Prof Dr H WINTER
Director,
Institut für Flugfuehrung, DLR
Deutsches Zentrum für Luft und Raumfahrt e.V. Flughafen
Postfach 32 67
D-38022 BRAUNSCHWEIG, GERMANY

DEPUTY CHAIRMAN
Dr T B CUNNINGHAM
Director of Technology
Honeywell Technology Center
3660 Technology Drive
MN 65-2100
MINNEAPOLIS, MN 55418, USA

TECHNICAL PROGRAMME COMMITTEE

CO-CHAIRMEN:	Dr G REID	UK
	DR E ZIMET	US
MEMBERS:	MR J B SENNEVILLE	FR
	Dr-Ing L CROVELLA	IT
	Dr-Ing B MAZZETTI	IT
	Mr B CAMPBELL	US

PANEL EXECUTIVE

From Europe:

AGARD-OTAN
Lieutenant-Colonel P FORTABAT, FAF
MSP Executive
7 Rue Ancelle
F-92200 NEUILLY SUR SEINE,
FRANCE

From the US or Canada:

AGARD-NATO
Attention: MSP Executive
PSC 116
APO AE 09777

Telephone: 33-1-5561 2280/82 - Telefax: 33-1-5561 2298/99

HOST NATION LOCAL COORDINATOR

Prof-Dr T V PAMPOUCAS
HAF Academy
22, Politeias Avenue
GR-14563 KIFFISIA (ATHENS)
Tel: (30) 1 801 4714
FAX: (30) 1 801 5184

ACKNOWLEDGEMENTS/REMERCIEMENTS

The Panel wishes to express its thanks to the Greek National Delegates to AGARD for the invitation to hold this Symposium in Athens and for the facilities and personnel which made the Symposium possible.

Le Panel tient à remercier les Délégués Nationaux de la Grèce auprès l'AGARD de leur invitation à tenir ce Symposium à Athènes et de la mise à disposition de personnel et des installations nécessaires.

Technical Evaluation Report

Thomas D. Taylor
Office of Naval Research
800 N Quincy St
Arlington, Virginia 22217, USA

INTRODUCTION

The 8th symposium of the mission systems panel was held to discuss the status of unmanned tactical air vehicles, which could deliver weapons. The meeting was composed of a keynote address and sessions on Applications, Operational Concepts, and Advances in UTA Techniques and Technologies.

The meeting provided a very good summary of the status of UTAs from an operational, systems, and technology point of view. The meeting revealed issues that have not been worked out and may well have cost implications for the UTA. These include air traffic control, survivability, reliability, integration with manned air operations, weapons delivery, weather, and collision avoidance. Many favorable characteristics make the UTA a promising field to pursue. These include low life cycle costs, low training costs, performance exceeding the limits of man in endurance and acceleration, reduced risk to life, and higher tempo of operations.

KEYNOTE ADDRESS

The keynote address given by Dr. L. Nicolai of Lockheed Martin Skunkworks was a valuable analysis of the anticipated life cycle costs of a UTA. The conclusion that the life cycle costs of a UTA can be as much as 50% less than a manned aircraft was a strong message to the audience and clearly, if true, will dominate the rational for development of the UTA concepts. The author advocated beginning with a clean sheet of paper in the systems design to attain these costs. The important feature that performance and design of a UTA did not have to be constrained by human limits in endurance, acceleration, vibration and temperature was also addressed. In addition it was pointed out that another attractive feature of the UTA was that an operator can be in the loop with little or no risk. The presentation was very positive regarding the value of the UTA. Some of the other papers were a bit more conservative in their enthusiasm.

SESSION 1 APPLICATIONS

This session contained 5 papers on various diverse subjects. The first paper presented by L. Ernst described the Predator UAV and its activity in Bosnia.The operational issues of an unmanned air vehicle were outlined. The air traffic control solution was a two-way radio for the operator who had to be a licensed pilot, a transponder, and a GPS position locator. To conduct the operations it was necessary to develop a de-icing system for the vehicle. The speaker pointed out that the predator was very survivable in operations because it flew too slow for weapon radar to detect

and flew high enough to avoid small arms fire.

A. Gatti made the second presentation of the session. The theme was to make use of sunk costs in aircraft and convert manned aircraft that were nearing the end of their usefulness to unmanned systems by adding the necessary sensors and guidance packages. This would allow test beds to examine the operational concepts and technology for future UTA applications.

The third paper was by R. Thevenot and A. d"Audiffret and addressed the topic of UTA surveillance of the battlefield. The paper focused on the value of the UTA for tactical ballistic missile defense and many of the associated operational problems. The paper was rather general in the discussion and mentioned many considerations that must be addressed for such a system, but did not attempt to specify the system.

The fourth paper was by G. Palfalvy, D. Andes, and D. Siegel and addressed highly maneuverable lethal vehicles. This paper lists many of the virtues of the UTA that have already been covered, however, there are two important areas that were emphasized. These are the reduced training since a pilot does not have to fly to train and the significant fact that the UTA weapons can be expected to be reduced in size due to the improved accuracy.

The fifth paper by B. Stewart addressed the operational effectiveness of UCAVs in mobile target attack. The paper is a general discussion of the UTA concept and brings forth the point that the vehicle should be considered a system of systems developed using a cost effectiveness analysis with different operational scenarios. The paper has no details.

OPERATIONAL CONCEPTS I

The first paper of this session examined design considerations for future UTAs. This paper was also a general overview of the UTA arena. The paper suggests that the driver for UTA development will be the significant decrease in military aircraft that will occur around the year 2010.The paper lists most of the advantages and concerns of UTAs that have already been discussed. Evaluation of the UTA concepts is proposed by using flying F-16 test beds and computer simulations to examine concepts of operation for both recon and strike type UTAs.

The second paper of this session was by H. Gilibert and R. Thevenor and focused on the HALE UTA with infrared sensors for theater missile defense. The paper outlines the parameters of a system to detect TBMs and points out that the HALE UAV with an IR sensor would meet the systems need very well. The paper indicates that the system is ideal because it flies above radar and missile intercept ranges and its sensors are passive. Also it flies above controlled air space so there is not an ATC problem. In summary the HALE system looks very interesting for the TBM role.

The next paper by D. Scheithauer and G. Wunderlich considers the systems integrity of UTAs. This paper is a qualitative overview of the subject. The paper discusses UTA missions and compares the UTA with the cruise missile and manned aircraft for these missions. Threats are also discussed along with UTA functional characteristics and system architecture.

The next paper of the session by R. Swartz, S. Millett, F. Rogers, and B. Hedman considered a joint semi-

autonomous air weapon system. In this paper there is a lot of discussion of the utility of their weapons system on UTAs.

The next paper by B. Shenk was very interesting. The paper discussed UTA design from an unconstrained maneuvering view. The paper points out that it is possible to design vehicles to exceed manned limits, but the greater the performance the more the cost and in some cases the technology understanding for conducting the design may need to be developed along nontraditional lines of thought. The paper also explains that if one drives the performance too high then the limits of flight control systems will be exceeded. This paper was one of the most quantitative of the presentations.

E. Fleeman presented a paper on sensor alternatives for UTAs. The paper discussed a variety of sensors including SAR, IR EO, passive mmWave, lidar, and a number of typical navigation sensors. The paper is informative if one is not familiar with this technology. A principal message from the paper is that weather and icing can seriously impact the use of most IR and optical sensors.

OPERATIONAL CONCEPTS II

The first paper of this session by I. Papachristofilou, P. Kaempf, and O. Wagner focused on certification and flight of UTAs in civil airspace. This paper provided an excellent overview of the steps needed to make a UTA acceptable to the civil air traffic control. They point out that a high reliability or low failure rate (~10-9/flt hr) is required. In addition the UTA must look like a manned aircraft to the ATC. It must fly IFR and VFR, have a collision avoidance system, be able to auto takeoff and land, and have a ground station at the operational airport. This paper makes it clear that the cost will be increased by the need to satisfy the compatibility with manned aircraft operations.

L. Serre presented the next paper on the subject of a hypersonic UTA. The idea presented was to employ a high speed UTA to perform rapid recon with IR and SAR sensors. Also to use the vehicle to stimulate enemy radars

A paper was presented by D. Deets on the subject of operational concepts for UTAs. The paper basically describes a number of unmanned flight test programs conducted by NASA. The message was be sure and involve the operator up front when you start a UTA program.

A paper was presented by R. Frampton on UTAs supporting offensive air operations. This paper provides a general discussion of the missions and roles of the UTA in combat operations. Many of the ideas are common to papers already discussed.

P. Faggion and L. Zolla presented a paper on autopilots for UTAs. This paper addressed the details of developing an autopilot for a UTA. The paper offers many details that a specialist will be interested in.

M. Henne and J. Baker presented the last paper of this session on the subject of mission re-planning for standoff weapons. This paper is a general tutorial on mission planning and re-planning. There is only a passing mention of UTAs in the paper.

ADVANCES IN UTA TECHNIQUES AND TECHNOLOGIES I

The last day of the meeting focused on advances in UTA techniques and technology. The first paper in this area was authored by M. Pelletier, A. Sakamoto, C. Tessier, and G. Saintonge

and addressed the CL-327 VTOL UAV that is currently under development in Canada. The vehicle is a propeller driven peanut looking shape, which is an enlarged/improved version of the CL-227. This vehicle appears to offer real promise as surveillance and targeting system, but may have problems with delivery of some types of weapons due to the geometry of the vehicle. The payload of the vehicle is approximately 200 pounds so it could deliver some small weapons.

The second paper of this session was authored by T. Kohler, F. Tumbragel, and J. Beyer and addressed a navigation system called RAPIN for future air-vehicles. The paper provides considerable detail and test results on the system for those interested in this technology.

The next paper was on modeling and simulation and demonstrated how it might be applied to control and guide a UTA. S. Furst, S. Werner, D. Dickmanns, and E. Dieter Dickmanns authored the paper. The paper was interesting, but the technology described has been operational in military systems for some time.

The paper presented by L. Bianchi, G. Battaini, G. L. Scazzola, and E. Crovari examined data links for UTAs. The paper provides a detailed discussion of the aspects of data link designs and also provides results obtained with a J band UAV data link.

A paper was presented by K-P. Gartner, and W. Kruger reporting the human performance associated with operation of a fiber optic link between a ground control system and a missile. The paper described the human response in target detection, classification and identification. Also the paper discussed the impact of the control system response time on the human performance. The paper was interesting since it relates directly to the technology used in both French and US missile systems.

ADVANCES IN UTA TECHNIQUES AND TECHNOLOGIES II

The first paper in the last session of the meeting was on the topic of UTA surveillance radar. F. Perret, J. M. Hermer, T. Gach, and E. Sicsik-Pare presented the paper. The paper described a Ku band radar-CRESUS-,that has SAR and MTI capabilities, which can be operated from a helicopter. The resolution was omitted from the paper, but it is believed to be on the order of one meter. The system appears light and small and looks like it would be a great value to operation forces.

J. Rau presented a paper on fault tolerant computer architecture. The paper is a very detailed discussion of technology of fault tolerant systems and how they may relate to UTAs.

M. Davenport, H. When, and I. Burke presented a paper on their work in management of imaging data for tactical airborne surveillance. The paper points out that a lot can be done with computers to aid the human in image interpretation. The main point was to use the computer for what it can do best such as tracking, help with target recognition, paste images together, and detect scene motion. They describe the areas that increased payoff can be attained.

The paper by S. Langham, and P. Zanker discusses UTAs from an electronic combat perspective. The paper examines the replacement of expensive HARM type missiles with UTAs to reduce costs. It covers requirements for SEAD operations in terms of the airframe and sensors. It also covers

threats and self-protection. In addition the topic of automated responses is discussed along with rules of engagement. The paper is a thoughtful discussion of the use of UTAs for strike.

The last paper of the meeting was presented by D. Brubaker and addressed small air to ground munitions for UTAs. The paper was very informative. It pointed out that the trends in technology are permitting small, lighter, lower cost weapons to be built which would be compatible with the UTA concept. The LOCASS weapon and the small smart bomb developments were discussed. The LOCASS is a small 100 mile range air vehicle with a jet engine and a programmable war head that is effective against vehicles and costs only about $25,000 each. The small smart bomb is a 250-pound highly accurate precision-guided munition that can be as effective as a 2000-pound bomb because of the small CEP. The reduced weight and size along the improved effectiveness have a significant impact on operations. The result will be fewer sorties, less collateral damage, less exposure to threats, and less overall operational costs. The main point to be gained from this paper is that weapons are changing and there are new concepts that will work well with the UTA concept.

PANEL SUMMARY

The meeting was closed with a panel discussion that reviewed most of the points already discussed. The main points were that system costs were still uncertain and many operational details remain to be worked out. The group however expressed positive views on the future of UTAs.

KEYNOTE ADDRESS

DESIGN GUIDELINES AND CONSIDERATIONS FOR THE UTA

Leland M Nicolai
Lockhheed Martin Skunk Works
1011 Lockheed Way
Dept 7212, Bldg 602
Palmdale, California 93599, USA

The Unmanned Tactical Aircraft is viewed by many as the centerpiece for affordable tactical air warfare in the year 2020 due to its potential for a revolutionary reduction in LCC and the fact that it embodies most of the Aerospace 2020 technology initiatives. Most of the technology for making the UTA effective as a weapon system is here today, but the technology for realizing its potential cost reduction remains to be developed.

UTA DEFINED

The definition of a UTA (or Uninhabited Combat Air Vehicle, UCAV) is any uninhabited vehicle that is recoverable and reusable with autonomous operation and man–in–the–loop that performs tactical missions. The man–in–the–loop feature is very important since there is always the possibility of an unknown or unforeseen event (inflight emergency, target not where or what it is supposed to be, hostages chained to the target, etc). The distribution of autonomous operation (preplanned in the near term and adaptive in the far term) versus man–in–the–loop is not known at present since the extent to which artificial intelligence or preprogrammed logic can accommodate unknown or unforeseen events has not been established. This automation technology is one of the enabling technologies that must receive significant attention in the future. The man–in–the–loop is a fall–back feature that permits a remote operator to interrupt the autonomous operation and assess the situation, make a decision and tell the UTA what to do next.

In the case of a UTA with weapons onboard, this man–in–the–loop feature permits the remote operator to make a rational, judgemental and moral assessment of the situation before the automatic weapons delivery. Onboard sensors would survey the target area and the target imagery would be data linked to the remote operator for target verification. This man–in–the–loop feature is often described as "removing the pilot's body from the vehicle but leaving his head onboard".

Paper presented at the AGARD MSP Symposium on "System Design Considerations for Unmanned Tactical Aircraft (UTA)", held in Athens, Greece, 7-9 October 1997, and published in CP-594.

The advantages of an uninhabited system over a manned system are:

1. Reduced Life Cycle Cost
    a. Lower acquisition
    b. Greatly reduced O&S
2. Human crew not at risk
3. Performance not tied to human frailties
4. Reduced political sensitivity

The reduced LCC is viewed as the most important benefit in this period of reduced defense budgets in the US. NATO's extreme interest in UTA is motivated by a similar trend towards massive reductions in the member countries' defense budgets. This benefit comes from reductions both in acquisition and O&S.

With the elimination of the pilot from the vehicle and the relaxation of the structural design criteria, the UTA can be made lighter, smaller and cheaper. For manned aircraft the crew station features account for approximately 6 percent of the empty weight and 2 percent of the unit cost. Eliminating the requirement for a crew station gives the designer more freedom in configuring and packaging a new UTA design. Relaxing the structural design criteria (lower factor of safety and reducing durability requirements due to reduced design life) can reduce the structural weight compared to a manned aircraft. Taking advantage of all the differences between the UTA and a manned aircraft, results in a "clean sheet–of–paper" UTA that has an empty weight reduction of approximately 40% and a unit cost reduction of about 50% relative to an equivalent mission manned aircraft.

In peacetime the UTA operator (or manager) trains using synthetic environment simulation. Since the UTA does not have to be flown during peacetime to maintain operator proficiency, there is a large reduction in peacetime O&S costs by not having the maintenance and support manpower costs. The problem is to have the maintenance and support personnel available during wartime but not have to pay for them in peacetime.

Since a human pilot is not onboard the UTA, the loss of human life is not a concern. This means of course that the UTA could be assigned missions deemed too risky for its manned counterpart.

The UTA can be designed for environmental conditions that are unacceptable for a human pilot. Maneuver g's greater than the human limit of nine are a design option as well as flight durations of days or weeks. Exposure to nuclear, biological and chemical environments would not be a major concern for the UTA. However, exposure to chemical or biological agents could be an issue if the UTA returns to base in a contaminated state. It would need to be decontaminated prior to its next mission or servicing task.

Since the crew has been eliminated from the vehicle, the political sensitivity of the UTA mission is reduced since there is no crew to be held hostage or crew remains to recover. In an extreme case, a country could deny ownership of a "laundered" UTA.

The class of UTA vehicles extends from more flexible and capable versions of currently deployed UAVs to future full spectrum uninhabited aircraft. Missions for UTAs in order of increasing complexity are as follows:

1. Intelligence, surveillance and reconnaissance (ISR)
2. Communications relay
3. Electronic warfare (jamming)
4. Air interdiction (fixed target strike)
5. Suppression of enemy air defenses (SEAD)
6. Theater ballistic missile and cruise missile defense
7. Air defense
8. Battlefield interdiction (mobile target strike)
9. Close air support
10. Air–to–air combat

The UTA configurations designed to perform the above missions can range from very small to very large with flight speeds from low speed to hypersonic. The elimination of the human from the vehicle opens up the design space enormously, giving rise to potential revolutionary configurations, capabilities and concepts of operation.

The first mission, ISR, is being demonstrated in several operational programs (ie; Predator, Phoenix, Crecerelle and Mirach 26) and development programs (ie; Darkstar and Global Hawk). Here the UTAs are "alone and unafraid", and doing the same recce missions as manned aircraft. These programs should fully establish the effectiveness of UTAs doing the ISR mission, however the cost advantage will need to wait for more system maturity and operational experience. The extended mission duration of Darkstar and Global Hawk should provide more cost effectiveness than the man–limited, 8 hour U–2 flights. The ISR UTAs would operate in both peacetime and wartime situations such that their cost savings in O&S would not be as dramatic as for a combat UTA.

The communications relay and electronic warfare are near term extensions of the ISR mission and naturals for the the UTA and its long duration capability. The electronic warfare UTA would need to interface and integrate with manned aircraft in the support jamming for strike elements.

The last mission, air–to–air combat, is the most complex and least understood mission for the UTA. At issue is whether the air–to–air UTA is really a "Robotic Wingman" or merely a recoverable missile, or somewhere in between. This would be a far term application for UTAs.

The air interdiction (fixed target strike) and SEAD missions appear to be the most interesting tactical demonstrations for the near term UTA as they involve dropping weapons and interfacing with manned strike aircraft in the conduct of very dangerous missions.

An excellent reference on UTAs is the recent report by the US Air Force Scientific Advisory Board (SAB) on the results of their six month study in 1996 on UAV Technologies and Combat

Operations (SAB–TR–96–01, November 1996). The SAB report recommends the first five missions listed above as the near term applications for UTAs.

PROPER VIEW OF UTA

The UTA is not a manned aircraft with the pilot removed. To view it as such limits the thinking to a manned aircraft experience in terms of design criteria, subsystems and equipment, training and support, operational deployment and most of all expectations. This thinking gives an evolutionary weapon system.

The UTA should be viewed as a revolutionary way of doing tactical air warfare. It should be viewed as a clean sheet design which never had a man onboard ... but man is in the loop. In addition the UTA might offer some revolutionary new tactical missions, other than those discussed on page 3.

Throughout the design of this new way of doing tactical air warfare the Lessons Learned from doing manned tactical air warfare should not be forgotten.

STRIKE UTA – A NOTIONAL CONCEPT AND PAYOFF

A Concept of Operations for a strike UTA doing a SEAD (Suppression of Enemy Air Defenses) and fixed target strike mission is shown in Figure 1. Since the strike UTA is a revolutionary concept, the Concept of Operations presented in this section is very preliminary and is offered as a departure point for further discussion.

The UTA is a complement to manned aircraft, not a replacement. There are many reasons for having a viable manned strike aircraft force. One point of view is that during peacetime and low tension situations, the strike UTA would probably not be flown, relying on the manned strike aircraft to project airpower and control situations. During wartime, the strike UTA would be deployed and conduct integrated tactical strike with the manned aircraft fleet.

Since the UTA is autonomous (with man–in–the–loop interrupt), it does not need to fly during peacetime for the operator to stay proficient. Thus, the UTAs are not flown during peacetime, but rather are stored in a humidity controlled, flyable storage facility. Eliminating peacetime flying reduces the peacetime O&S costs significantly. To ensure readiness, several UTAs would probably be taken out of storage and flown each year for training exercises, but the total 24 unit squadron flying hours would be less than 100. In contrast, a 24 unit F–16 air–to–ground squadron would fly about 8300 hours each year.

Since the UTA is essentially not flown during peacetime, the number of active duty ground crew (maintenance and support personnel) is very small. During peacetime, the ground crew would support the few actual flights, maintain the UCAVs in flyable storage (assumed to consist of monthly external inspections), and train reserve ground support crews. This UTA concept is very much different than the concept for manned aircraft. Manned aircraft must be operated regularly in peacetime in order to maintain aircrew proficiency, exercise avionics and weapon systems, and keep

MISSION AREA: SEAD AND FIXED TARGET STRIKE

FEATURES:

INDEPENDENT OR INTEGRATED WITH MANNED STRIKE

AUTONOMOUS MISSION WITH MITL FOR AUTHORIZATIONS

GREATLY REDUCED PEACETIME O&S
- **AIRCRAFT IN FLYABLE STORAGE**
- **MINIMAL FLYING (ANNUAL SQUADRON FLYING)**
- **REMOTE PILOT PROFICIENCY THRU SIMULATION**
- **GROUND SUPPORT CREW PROFICIENCY THRU TRAINING DEVICES AND FEW ACTUAL FLIGHTS**

SEPARATE BASING WITH HIGHLY AUTOMATED GROUND HANDLING (SMALL MANPOWER REQUIREMENT)

AIRCRAFT DESIGNED FOR 500 HRS STRUCTURAL LIFE AND MAINTENANCE FREE OPERATION

Figure 1. Notional Concept of Operations for a strike UTA

the aircraft in flying condition. The active duty UTA ground crews are estimated to consist of less than 20 people per squadron in peacetime. In contrast, the F–16 squadron requires over 240 ground crew personnel to support the peacetime flying operations of 24 aircraft. When the UTA is deployed during wartime, the ground support crew would be augmented by reserve crews.

The UTA system would be designed so that it can be deployed during wartime needing only a fraction of the ground crew personnel required for a manned strike aircraft unit. The UTA airframe and equipment are designed to a limited life ... time spent in actual wartime. A manned aircraft is designed to something like 7000 hours (15 year lifetime with 30 hours of training per month plus 1000 hours of deployment and 500 wartime hours) whereas the UTA is designed to only the wartime hours. Both the structural design life and the equipment life of the UTA is designed for about 500 hours. The equipment would have a design goal of operating maintenance free for 500 hours. Scheduled maintenance (replacement of brakes, tires, batteries and POL) would be performed during wartime, but no unscheduled maintenance. This 500 hour maintenance free operation greatly reduces the number of ground crew personnel needed in wartime since no maintainers are needed.

In addition the UTA ground handling would be highly automated so that the active duty ground crew plus 4 reserve unit ground crews can support the wartime operation of a 24 unit strike UTA squadron. A ground handling concept would consist of automated ground equipment and activities. The UTA would taxi around the airfield under its own power following a ground map and plan (using differential GPS) under the control of a ground operator.

A conceptual design was conducted of a near term strike UTA having requirements similar to an F–16C in order to quantify the projected LCC savings. This study permitted a one–to–one cost comparison with a current manned strike aircraft. The UTA had an empty weight of approximately 7000 lb and a unit flyaway cost of $7M in 1996 $ (the resulting ratio of empty weight to unit flyaway cost is $1000/lb and is about ten percent less than that for a manned aircraft).

A 24 UTA squadron manning for peacetime is shown on Figure 2 and compared with a 24 strike F–16 squadron. The number of officers (primarily pilots or remote operators) is about the same for the two stike squadrons, but the number of enlisted personnel doing maintenance and support is very much less for the UTA squadron. The UTA peacetime O&S cost is an order of magnitude less than a comparable manned squadron for this near term example.

F–16 Annual O&S (per AFI 65–503)		Strike UTA Annual O&S (per modified AFI 65–503)	
Unit personnel (42 off./307 enl.)	$14.3M	Unit personnel (30 off./32 enl.)	$3.25M
Fuel for 8300 flying hours	5.0M	Fuel for 100 flying hours	.06M
Personnel support	9.2M	Personnel support	1.31M
Depot maintenance	6.1M	Training and personnel acq	.63M
Training and personnel acq	4.8M	System support and mods	.60M
Replenish spares	6.0M		
System support and mods	3.9M		
Munitions and missiles	1.1M		
Total	**$50.4M**	**Total**	**$5.85M**

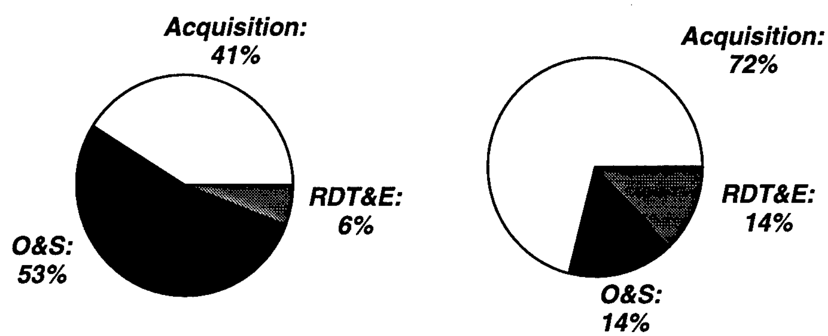
Figure 2. Strike UTA Peacetime Operation and Support Cost Compared to F–16 Unit (1996 $M)

The projected 10 year life cycle cost for a UTA squadron is shown on Figure 3 in comparison with a strike F–16 squadron. The squadron amortized RDT&E and acquisition costs are about the same for the two squadrons. The UTA acquisition cost includes the unit cost of $7M each plus 6 ground stations and the ground support equipment (GSE) for the automated ground handling. The big difference is in the O&S cost which gives a greater than 50% reduction in 10 year LCC for the UTA. It is expected that a year 2020 UTA, "pushed" by an ambitious technology program, would exceed this LCC savings significantly.

The technology areas critical to developing a strike UTA are:

1. Communication and control architecture
2. Adaptive autonomous vehicle control systems
3. Man/Machine Interface – extent of autonomous operation vs man–in–the–loop
4. Near–real–time, secure, long range data communication
5. Reduced manpower for operation and support
6. Long term storage of engine and vehicle systems
7. Automated ground handling and launch/recovery
8. Extended maintenance free operation

Squadron:	**F–16 C/D Manned**	**Strike UTA**
No. of Aircraft:	**24**	**24**
Peacetime Annual Flying Hrs:	**8300**	**< 100**
Squadron Amortized RDT&E:	**$60M**	**$60M *($2B est. over 33 squadrons)***
Squadron Acquisition Cost:	**$381M**	**$310M *(24 UTA @ $7M each, 6 ground stations @ 13.7M each, $60M GSE)***



Annual O&S	**$50.4M**	**$5.9M**	**(all $ in 1996 $M)**
Total 10 Year LCC	**$945M**	**$429M**	

Figure 3. Ten Year LCC Comparison

9. UTA structural design criteria
10. Lightweight/limited life structure

The first four technology areas are absolutely critical as they put the "U" in UTA. The technology areas number 5 through 8 are the business motivation for the UTA as they reduce the peacetime O&S costs. The last two reduce the airframe weight of the UTA which reduces the acquisition cost.

DESIGN GUIDELINES AND CONSIDERATIONS

GUIDELINE #1: THE UTA IS NOT A MANNED AIRCRAFT WITH THE PILOT REMOVED

Since the UTA is a new concept, we must start with a clean sheet of paper and not be held hostage by tradition. As we said earlier, *the UTA is <u>not</u> a manned aircraft with the pilot removed.* To view it as such limits the design and operational concept to a manned aircraft viewpoint – in terms of design criteria, subsystems and equipment, training and support, operational deployment and mission expectations. This type of thinking yields an *evolutionary* weapon system. The UTA should be viewed as a *revolutionary* way of doing tactical air warfare. It should be viewed as a clean sheet design which never had a man onboard – but man is in the loop. During the development of this

type of vehicle, the design and operational lessons learned from manned systems should not be forgotten.

GUIDELINE #2: THE UTA IS A COMPLEMENT TO MANNED AIRCRAFT, NOT A REPLACEMENT

The UTA is a <u>complement</u> to manned aircraft, <u>not a replacement.</u> There are many reasons for having a viable manned aircraft force. Even though the UTA will dominate the ISR mission, there will be a need for a mix of combat UTAs and manned aircraft. One point of view is that during peacetime and low tension situations, the strike UTA would probably not be flown, relying on the manned strike aircraft to project airpower and control situations. During wartime, the strike UTA would be deployed and conduct integrated tactical air operations with the manned strike aircraft fleet.

GUIDELINE #3: THE MAJOR DESIGN CONSIDERATION IS REDUCED COST

The major design consideration must be to design the UTA to conduct tactical air warfare at a *reduced cost*. If the UTA does not have reduced cost for similar effectiveness as a manned aircraft ... <u>It Will Never Happen!</u> There must be a compelling reason for the manned aircraft community to trust their missions to a UTA. Reducing the cost of conducting tactical air warfare by the levels possible with the UTA is a compelling reason.

All of the following design considerations support the *cost reduction* potential of the UTA.

1. DESIGN FOR: TRAINING WITHOUT FLYING THE VEHICLE

The proficiency training for the remote operator(s) is transparent to whether the UTA is flying or not. Therefore, the UTA system should be designed for peacetime training without having to fly the vehicle. The number of remote operators in the UTA unit during peacetime would be at the wartime level and they would train using synthetic environment simulation. However, by not flying the UTA, the number of maintenance and support personnel needed during peacetime would be small. These few maintenance and support personnel would remain proficient by using ground training devices and in turn would train reserve crews for wartime augmentation. This is a very important feature if the potential for reducing peacetime O&S is to be realized.

2. DESIGN FOR: LONG TERM STORAGE

If the system has been designed to not be flown during peacetime, then the vehicle will need to be designed for long term storage. Ideally, one would like the vehicle to be put into a storage facility with no maintenance required and then respond instantly when needed. Our experience with Harpoon/SLAM and Tomahawk cruise missiles indicates that we need to provide a humidity controlled facility and to carefully select the equipment items. Whether or not the vehicle is stored with fuel, weapons, batteries and full–up avionics is still an open question.

3. DESIGN FOR: AUTOMATED GROUND HANDLING AND L&R

The UTA system should be designed for autonomous (or at least semi–autonomous) ground handling and L&R (launch and recovery) during flying operations. This will reduce the number of people required to support the aircraft during combat. A careful study needs to be done early that examines the L&R concept: CTOL (conventional take–off and landing) vs rail launch/parachute recovery vs TBD. The rail launch/parachute recovery is manpower intensive and there is always damage with a ground impact parachute recovery. If the vehicle is very large (ie; several thousand pounds), automatic CTOL is a lower cost solution. For a CTOL UTA, the vehicle would taxi under its own power following a ground map and programmed instructions. The support functions of vehicle systems check–out (health status), down loading new mission information, rearming and refueling would be as automatic as possible. Replacing tires, brakes, POL, filters, batteries and other minor LRUs would still be human tasks. The automated ground handling feature will involve some UTA unique ground support equipment.

4. DESIGN FOR: EXTENDED MAINTENANCE FREE OPERATION

If the UTA were designed for 250 to 500 hours of maintenence free operation (except for replacing tires, brakes, POL, batteries, filters and other minor LRUs), the maintenance and support personnel could be reduced significantly relative to a manned aircraft unit. The 250 to 500 hours would be the flight hours for a typical "war". This feature would mean that the manpower and spares that were needed to go to "war" would be small. The manpower and spares would be only that needed to "turn" the aircraft for combat sorties. At the end of the typical "war" the UTA could be refurbished by replacing (or upgrading) many of the major equipment items. The designer would need to design in redundancy and carefully select the equipment items for high reliability. The customer will need to be prepared to pay extra for this extended maintenance free feature in the acquisition cost of the UTA.

5. DESIGN FOR: REDUCED DIRECT MAINTENANCE MANHOURS PER FLYING HOUR

This design consideration is always good whether the aircraft is manned or unmanned. It is especially important for the UTA because the number of maintenance personnel available to go to "war" will be limited since they are not needed during peacetime. The replacement of tires, brakes, POL, batteries and minor LRUs would be designed for a "pit stop" quick change. The UTA will need extensive onboard diagnostics to monitor and report the health and status of the vehicle.

6. DESIGN FOR: UTA UNIQUE STRUCTURAL CRITERIA

The structural criteria for the UTA will be different than for a manned aircraft. Since the UTA would do limited flying during peacetime, it would be designed for a shorter design life to cover only the actual time in combat. This could be 500 to 1000 hours (ie; two "wars" during a 10 year vehicle lifetime). Also, the UTA would have a factor–of–safety of 1.25 instead of the 1.5 for manned aircraft. Since the UTA would not be limited by a human onboard for altitude, endurance, temperature, vibration and maneuver g limits, the structural design envelope can be greatly expanded.

7. DESIGN FOR: DEPLOYMENT

The UTA system must be designed for easy deployment after having been in storage for extended periods. A careful trade study needs to be done very early looking at the movement of the UTA vehicle and the unique ground support equipment (GSE) required for combat. The UTA could be flown to the deployment area using inflight refueling or transported in a large transport aircraft. Aerial refueling is a good feature regardless of the deployment concept. Transporting the UTA in another aircraft will impose design constraints on the vehicle that need to be addressed. The unique GSE could be pre–positioned or designed for easy transport in transport aircraft. The deployment air bases would be surveyed in advance and the autonomous ground handling plans prepared.

8. INCORPORATE THE GOOD DESIGN FEATURES AND TECHNOLOGIES FOR MANNED AIRCRAFT INTO THE UTA

The UTA is an aircraft and F=ma for it as well as the manned aircraft. Thus, what is good for the manned aircraft is also good for the UTA (ie; drag and fuel consumption reduction technologies, small smart weapons, and high strength, lightweight materials). The reverse is true here also. Many of the design features for the UTA are applicable to manned aircraft to reduce their LCC.

SUMMARY

The design guidelines and considerations for making the UTA a reality have been discussed. The extent to which the UTA advantages are realized is as much a cultural challenge (how it would be implemented) as it is a technology challenge (what can the warfighter have). Since the impact of the UTA is a revolutionary reduction in the cost (both financial and human lives) of conducting tactical air warfare, it is imperative that both challenges be met.

ACKNOWLEDGEMENT

Special thanks goes to Mr. Allan Hill of Lockheed Martin Tactical Aircraft Systems, Ft. Worth, Texas for his unique ideas on the strike UTA support concept.

From Manned to Unmanned: a Viable Alternative to the Scrapyard

A. Gatti
Product Development
Alenia Aerospazio
Product Development
Corso Marche 41, 10146 Torino, ITALY

SUMMARY:

Analysing the different scenarios currently considered by NATO (Peace keeping, Out of Area, Counter Proliferation, Article 5) requirements of weapon systems at the same time precise, lethal, with a great stand-off range and endurance capability emerge. Budget, humanitarian and political needs together with improvements in technolgy suggest that un-habitated systems will become the best answer to those requirements.

Italian Air Force still operate a large number of F-104s that within few years will be phased out. The conversion of F-104s into autonomous and recoverable unmanned vehicles able to perform ground attack or SEAD missions, or into an high-altitude reconaissance platform is feasible and seems an actractive and affordable way to develop an effective hardware able to safely operate in mixed air operations in which manned and unmanned planes share different roles.

ACRONIMS & ABBREVIATIONS

A/C	Aircraft
AMI	Aeronautica Militare Italiana (Italian Air Force)
EO	Electro Optical
GPS	Global Positioning System
HALE	High Altitude Long Endurance
INS	Inertial Platform
IR	Infra Red
IRSTA	Intelligence Reconaissance Target Acquisition
Kft	Kilo Feet
LOROP	LOng Range Oblique Photography
NFCC	Navigation and Flight Control Computer
RX/TX	Receiver/Transmitter
SAR	Sinthetic Aperture Radar
SEAD	Suppression of Enemy Air Defences
TAS	True Air Speed
TBM	Tactical Ballistic Missile
UCAV	Unmanned Combat Air Vehicle

1 INTRODUCTION.

Since the collapse of the Warsaw Pact, deep changes have arisen in warfare operational concepts, weaponry and criteria of political approval about force application.

Governments increasingly face the contradictory needs of managing military operations achieving the target they are aimed to, without suffering any fatal casualty and/or inflicting any unintentional damage to the hostile party.

Budget constrains set at the same time the necessity to keep training and acquisition costs as down as possible suggesting that the only conflict a Western Coalition can sustain without loosing its public opinion's support and its finacial stability is a "zero casualties-zero costs" one.

In all the different scenarios currently considered by NATO (Peace keeping, Out of Area, Counter Proliferation, Article 5) the need to reduce collateral damage is driving to the need of weapon systems at the same time precise, lethal, with a great stand-off range and endurance capability.

The conversion of ageing combat aircraft into autonomous and recoverable unmanned vehicles able to deliver precision weapons seems actractive being capable of covering different missions at competitive costs when compared with highly sophisticated and dedicated stand-off weapons.

2 OPERATIONAL LIMITATIONS AND NEEDS.

To identify the requirements of future systems an analysis based upon the scenarios related to operations of Peace Keeping, Counter Proliferation, Out of Area and Article V has been performed.

Results of this analysis show that, although the level of the Anti Aircraft threat was very influenced by every specific scenario considered (ranging from quite low in Peace Keeping operations to very high in Counter Proliferation operations), anyway the

Paper presented at the AGARD MSP Symposium on "System Design Considerations for Unmanned Tactical Aircraft (UTA)", held in Athens, Greece, 7-9 October 1997, and published in CP-594.

accuracy required on weapons delivery was always very high in order to minimise the risk of collateral damage (Peace Keeping), guarantee an high lethality during a single-raid operation (Counter Proliferation), reduce the time required to reach a planned operational target (Out of Area and Article V).

A direct consequence is that the Circular Error Probability of the weapon has to be as low as possible (tipically below 15 ft) and the confidence level on target identification is to be very high. This last aspect implyes the availability of a very efficent Intelligence Reconaissance Surveillance and Target Acquisition system and a very capable Target Identification system placed on the weapon delivery platform.

Therefore two typical platforms can be identified:

- with long endurance and high altitude for IRSTA (HALE);
- able to fly at very low altitude for direct attack (UCAV).

Both of these roles suggest the use of non-habitated platform in order to avoid a serious physical stress in the first case and a very dangerous risk esposure in the second.

The first role would lead to very dedicated unmanned platforms (HALE) whilst the second can lead to both the use of cruise missiles featuring very sophisticated systems for target acquisition and identification, or to recoverable UCAVs able to deliver very precise weapons (stand-off or short range) and perform Recce missions.

2.1 Requirement on HALE.

HALE A/Cs can provide long range surveillance over wide areas and look deeply into hostile territory taking advantage of the extended line-of-sight against earth curvature and terrain obstacles for monitoring sites and/or launch phase of TBMs or cruise missiles as well as to control other suspect activities (Stand-off Surveillance and Early Warning) or cueing forwardly deployed engagement systems (aircraft, ships, etc.). Flexibility typical of aerial platforms will grant rapid deployment and repositioning whereas long endurance should be a requirement for getting the maximum operational easiness and the minimum total cycle cost (fleet size, crews, logistics, training, etc.).

Loitering altitude should be well above commercial air traffic (> > 60kft), loitering speed (perhaps close to 200 kt TAS) shall be set by maximizing endurance once SAR minimum speed, the presence of adverse jet-streams and the detection of slow moving target with MTI radar have been taken into account. Typical operational range (distance from airbase to loitering station) should be in the order of 500-1000 Km, the maximum range being limited by line-of-sight range between the A/C and its Control Station, the use of a midway data-link (A/C or satellite) allowing longer range operations.

Several sensor/payload packages will be required in order to perform different missions. Depending upon the size of the platform they will be combined together to enhance mission capability.

- EO/IR Sensor,

for Reconaissance and Surveillance of generic targets both fixed and mobile.

- MTI/FTI Radar (SAR),

for monitoring of suspect activities, track mobile ground targets.

- ELINT/SIGINT equipment,

for monitoring communication and electronic activities.

- Trasponder / repeater equip.:

for telecommunication relay in order to rapidly expand C^3 function, expecially for out-of-area operations.

Different dedicated payloads would enable even civil application as Exclusive Economic Zone monitoring, narcotic smuggling repression, weather reconnaissance, earth and sea observation, agricultural/forestry mapping, pollution monitoring.

A total mass of the payload (sensors, recording system, data link) of 1000 Kg is realistic.

2.2 Requirement on UCAV.

The platform for the low altitude attack role is, from any practical standpoint, an attack aircraft except for not having any pilot onboard. It should permit the carriage and delivery of at least two precision weapons in the 1000 Kg class or of two HARM missiles over a 500 km range and be compatible with the carriage of Recce pods.

3 UN-HABITATED: Autonomous or remotely controlled?.

When dealing with the concept of "un-habitated" a basic distinction occurs between an almost autonomous vehicle and a remotely controlled one. The attribute of "almost" is due to the necessity of giving to a human operator the capability to supervise what an automatic system is going to do before any critical decision (i.e. involving the use of weapons). For the most part of its flight the system will behave in total indipendence, just relying upon its capability to set an appropriate flightpath, route and a correct "tactical" behaviour.

Such a capability, that can be considered a sort of "artificial tactical mind", must be able not only to fly over a corrugated landscape, functionality that is already available as a state of the art one, but also to be able to acquire, locate and identify critical items as potential targets or threats and take a proper decision about its flightpath and behaviour (use of the weapons, etc.).

Therefore the system has to be able to perform in real time a process of objects identification based on its sensors (TV,IR, etc.) output and then to properly identify the tactical situation existing in that moment in order to get a situation awareness. Finally it must be able to decide how to change its flightpath, taking into account: the goal it was assigned to, its energy (altitude, speed, fuel remaining, etc.), threat avoidance, etc..

Key technology of the system will be the use of concepts like those of "fuzzy logic" and "neural network" for image and situation automatic recognition.

An alternative approach is the remote control of the platform, using for example a data-linking, by a human operator eventually supported by an automated system by far greatly simplified with respect to the fully automated one. In this case the main scope the system has to fulfil is the navigation and flight control, in terms of attitude holding, of the platform.

Pondering the current technology status in cybernetics, software and hardaware availability the second approch has been thought as more realistic and able to generate operation systems in the middle term.

4 THE F-104 in the Italian Air Force.

The development of the F-104 (fig 4-1) began in 1951, its G version flew in October 1960 and the S followed in December 1966. The aircraft was produced on two continents, the American and the European, with a total exceeding 2500, and were in service in 14 countries worldwide. The F-104 was considered as an exceptional interceptor type and still retains this classification among modern day aircraft.

The Italian Air Force used more than 160 F-104G produced in Italy under Lockheed license and currently is still operating more than 150 aircraft of a total of more than 200 delivered since 1969 in the S version which was co-produced with Alenia (at that time Aeritalia) till 1977.

The last modernisation plan, involving more than 100 aircrafts is currently in progress.

The phasing out of the F-104 is foreseen to happen for the year 2005 being the Starfighter replaced by the EF-2000.

At that time more than 100 F-104 will be available in Italy (and more than 600 all over the world in flying or storage condition) for conversion in unmanned aircraft or for the scrapyard.

F-104S Main Characteristics	
Length	16693.9 m
Span	6687.3 m
Wing Surface	18.22 sqm
Emty Weight	6760.5 Kg
Design Weight	9815.0 Kg
Payload	3054.0 Kg
Operational Empty (with pilot)	7503.9 Kg
Internal fuel	2869.0 Kg
Underwing tanks	1211.1 Kg
Tip tanks	1435.2 Kg
Thrust	dry: 52.8 KN with AB: 79.0 KN

The aircraft is fitted with two engine-driven 20KVA 115/200V variable-frequency (320-520Hz) generators and a 2.5 KVA 115/200V fixed frequency generator driven by an hydraulic engine. A trasformer/rectifier unit and two nickel-cadmium batteries provide to 28V DC supply.

For armament carriage a total of 9 attachment points is available (at wingtips, under wings and under fuselage).

5 MODIFIED UN-HABITATED VERSIONS.

Two different levels of modification have been identified:

- Mainly focused on hardware and software integration in order to make the aircraft able to perform, without any human on board, missions whose profiles are very similar to those it was in origin designed for (UCAV).
- Of greater extent and larger impact on the aircraft configuration itself in order to cope with brand new mission profiles like those of an high altitude Recce aircraft (HA-UAV).

5.1 Unmanned Combat Air Vehicle.

This version (fig 5.1-1) is aimed at performing high risk, low altitude missions as Recce flights or ground attacks using anti radiation missiles for SEAD or eventually as delivery platform of guided or stand-off weapons.

To accomplish Recce role the best way is the integration of any EO/IR Recce Pod connected through the aircraft Data-Link to the ground rather than the installation of dedicated sensors inside the aircraft.

Integration of a target designation system (LCDP pods or equivalents) for weapon guidance is not considered cost effective and the best used in direct ground attacks with guided munitions will be just carry and release the bombs whereas the designation will be performed by a less exposed aircraft.

The most promising use of an unmanned F-104 is the launch of Anti Radiation Missiles during SEAD attacks. Each aircraft can carry up to 4 HARM or equivalent missiles that could be initialized via data-link by a SIGINT/ELINT aircraft orbiting in a stand-off position or a Tornado ECR class aircraft flying at a safe distance from the unmanned-intruder.

- Configuration changes

The airframe will be modified removing by the front part of the fuselage the cockpit, pilot seat, radar, gun and related accessories. The guidance system, additional sensors (TV/IR, GPS, etc.) and data-link antennas will be housed into a new semi-flush radome replacing the canopy (figs 5.1-2, 5.1-3). The nose cone will be not changed in shape in order to avoid the re-tuning of the air data sensors.

Taking into account the removal of furnishing and equipments (ejection seat, oxigen bottles, displays, etc) a weight reduction of 160 kg. is realistic without heavy impacts on the airframe. Deletion of M-61 gun, ammunition and cases would save 340 kg and some further 170 kg will come from Radar and avionics.

The new avionics and sensors will add a total of 160 kg.

Additional fuel tanks can be housed in the fuselage inside the gun bay (130 Kg), the ammunition stowage compartement (225 Kg) and the cabin (450 kg).

Anyway additional evaluations have to be performed in order to assess if benefits in range are worthy this quite costly modification.

- Avionics and Control System

The navigation and fligh control system will be based, to keep down costs and complexity, on only two indipendent computers one of which on-duty and the other in stand-by. Switching from one unit to the other will happen as a consequence of a failure evidenced by a built-in test procedure perhaps enhanced by further specific built-in tests activated via data-link.

Navigation and attitude control will be performed by NFCC using position and attitude data coming from the IN/GPS unit which is duplicated for redundancy whereas angle of attack, speed and barometric altitude will still come from the current sensors. Special interfaces will be required to make engine parameteres able to be input into the NFCC.

- Data Link

The data link is intended to be MIDS standard with an additional hardware to connect the system via-satellite with the italian military communication sistem (SICRAL). The need to send images generates high data rates which impose the use of dedicated computers for image/signal compression.

To control the aircraft the automatic system will act on the current control lines (rods based, hydraulically powered) for rudder, ailerons , elevator and engine throttle using additional electric actuators in very close analogy with classical drone conversions (OF-104).

By an operational point of view, the excellent bisonic design of the F-104 has no reason to be changed even if the Mach 2+ performance relevant to the clean aircraft (without wing tanks and at high altitude) will be not exploited any more, whereas penetration speed at sea level of 500 Knt a the very low gust sensitivity are more than adequate even for the unmanned variant.

F-104S UCAV Main Characteristics	
Length	16693.9 m
Span	6687.3 m
Wing Surface	18.22 sqm
Emty Weight	6160 Kg
Payload	3054 Kg
Internal fuel (* with additional tanks)	2869.0 Kg (3674.0 *)
Underwing tanks	1211.1 Kg
Tip tanks	1435.2 Kg
Thrust	dry: 52.8 KN with AB: 79.0 KN

5.2 High Altitude UAV.

This version (fig. 5.2-1) is aimed to cover the role of high altitude, long range, Recce or ELINT aircraft.

By an historical standpoint, conversion of F-104 into an high altitude reconaissance aircraft it is not new, this modification having been the base of U-2A prototype. For the HA-UAV, modifications of that extent are not realistic being their cost absolutely not worthy when compared with the intrinsic value of a 30 years old airframe. Therefore the modification has been conceived as the minimum required to enable the aircraft to carry a payload of 1000 Kg at 20-21 km of altitude and speed of Mach 0.75-0.80.

To get the aim it is intended to, on the High Altitude UAV, Starfighter's fuselage has to be matched with a brand new, high aspect ratio, wing. This wing will be based upon supercritical airfoils with thickness-to-chord ratio of 9-10% and a sweep angle at the leading edge of 14°. Flaperons will be present on the trailing edge.

The largely different lift-incidence slope of this new wing compared with basic wing's one directs a great configuration change of aerodynamic control surfaces to enable again longitudinal stabilisation and trim. To preserve the longitudinal static margin and guarantee good dumping characteristics, the horizontal tail surface has to be drastically enlarged, its aspect ratio increased and its profile changed with respect to the current layout thus leading to the costruction of a brand new unit. The vertical tail will be deeply modified too: the rudder geometry being enlarged and an high aspect ratio tip added at the top of the fin.

The existing undercarriage will not be altered but integrated with two small retractable outriggers on the wing in order to avoid structural overstressing during take off and landing and to ease the control in the event of crosswind during approach/landing

The front part will be modified just as the low altitude version.

Additional fuel (some 4200 litres) will be stored in the wing.

RECCE equipment will be housed in the forebody and it will consists of a long range elettro-optical sensor for LOROP and an IR line scanner or, as an alternative, of a SAR equipment.

F-104S UCAV-HA Main Characteristics	
Length	16693.9 m
Span	21.0 m
Wing Surface	41.0 sqm
Emty Weight	7000 Kg
Payload	1000 Kg
Internal fuel	7200 Kg

6 OPERATIONAL CONCEPTS.

The main issue about using unmanned aircrafts in an open air-space (and not inside a firing or test site) is the accomplishment of safe operational conditions for all the other planes flying inside the radius of action of the UCAV as well as for people and properties on the ground.

The best way to solve this problem seems to:

1 use a pre-programmed flight route based upon waypoints, the route will be send (encripted) via MIDS to all the other platforms sharing a given air-space with UCAV together with the designation of the UCAV as un-habitated;

2 directly control the aircraft during take-off/initial climb and approach/landing using a remote operator on the ground;

3 monitor the flightpath routinely during the cruise phase, in the event of an engine failure an automated, real-time, mission replanning has to performed on ground and sent to the UCAV heading it to a safe impact point.

4 during the penetration phase, control authority can be left either to the on-board automatic system with remote supervision using satellite data-link, or switched to a human operator onboard an aircraft loitering in a safe position.

5 it is mandatory not to engage directly the target using unguided or self-targeting weapons due to the difficulty of the acquisition and aiming process even by a remote human operator but use guided weapons whose target illumination was peformed by an external human operator.

If during any of these phases the aircraft would go out of control and no recovery action could be taken a self destruction system will be activated.

To conclude: in the middle term air operation entirely based upon un-habitated vehicles are not realistic, mixed manned/un-habitated planes operations seem by far more feasible.

As an example, when considering the inventory of aircrafts of the Italian Air Force, two different platforms could be soundly designated as able to house the airborne manned-part of the system.

- The Tornado ECR for SEAD high-risk missions: the aircraft can fly behind the UCAVs and use its electronic sensors suite to discover, identify and locate the radar threath, then using the data-link can initialize and fire the UCAV-carried anti radar missiles under the control of the Tornado system operator.
- The AMX in its two seats variant for close air support operations: the manned aircraft can loiter at a safe distance, at medium-high altitude, from the target and use a designating laser system (es: LCDP pod) whereas the UCAVs will simply carry the laser guided weapons and release them under the control of the weapon operator onboard the AMX.

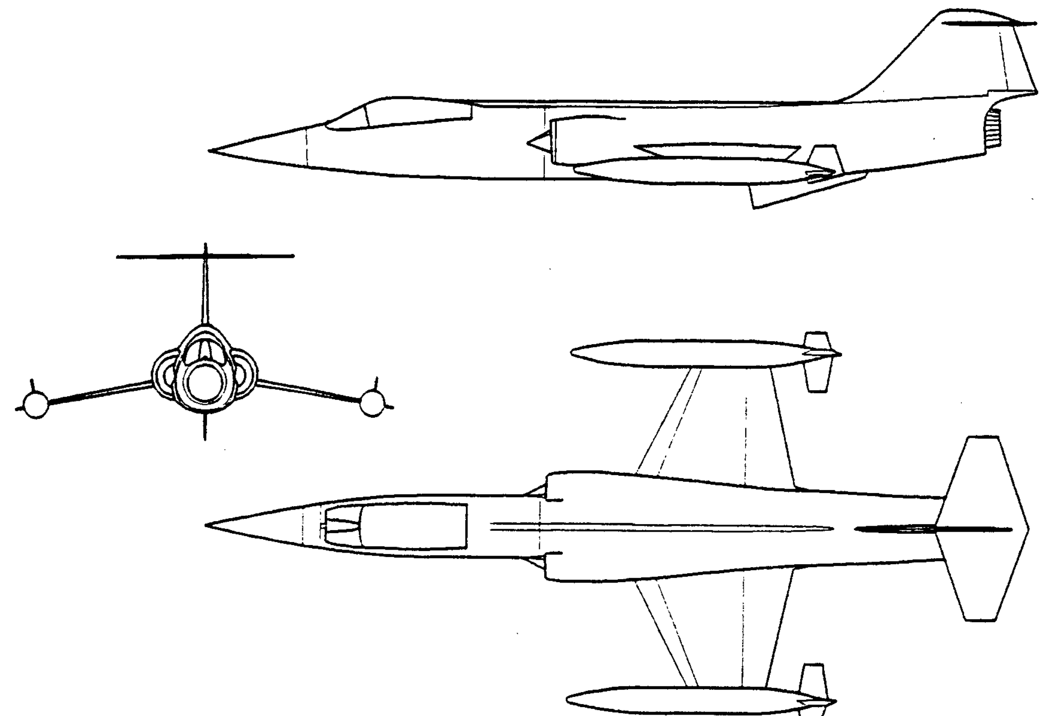


Fig. 4-1

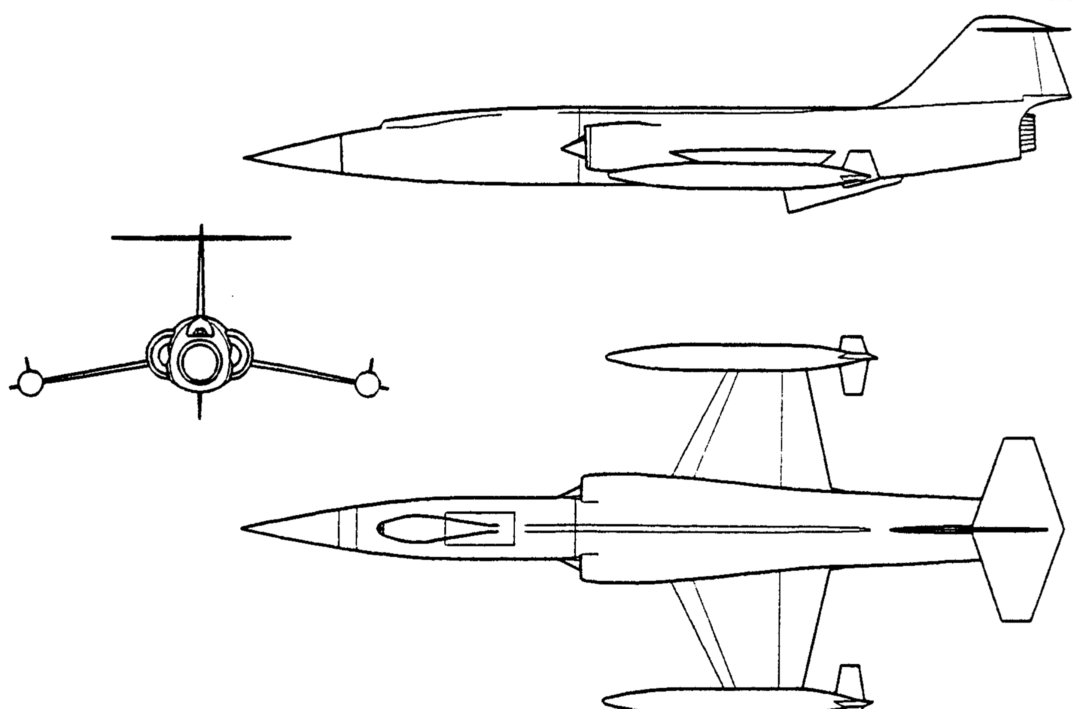


Fig. 5.1-1

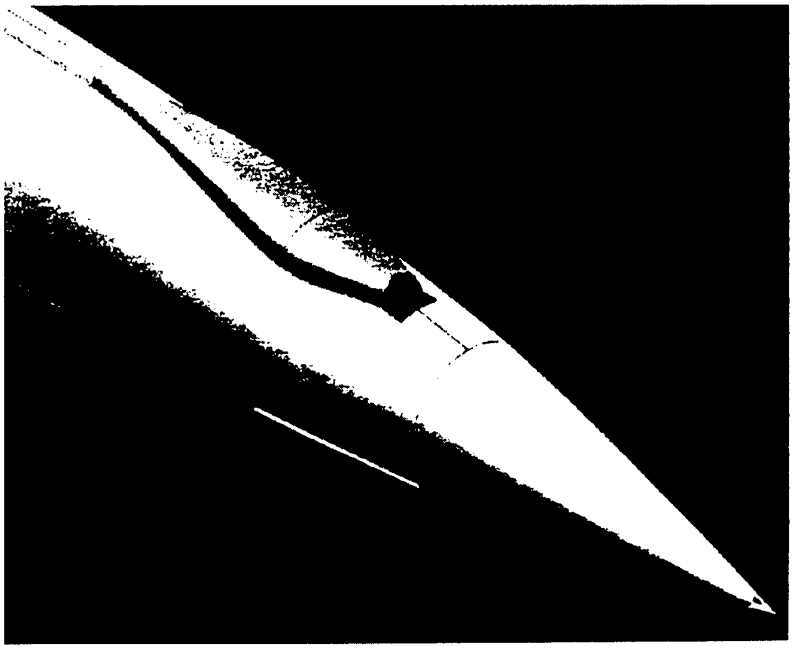


Fig. 5.1-2

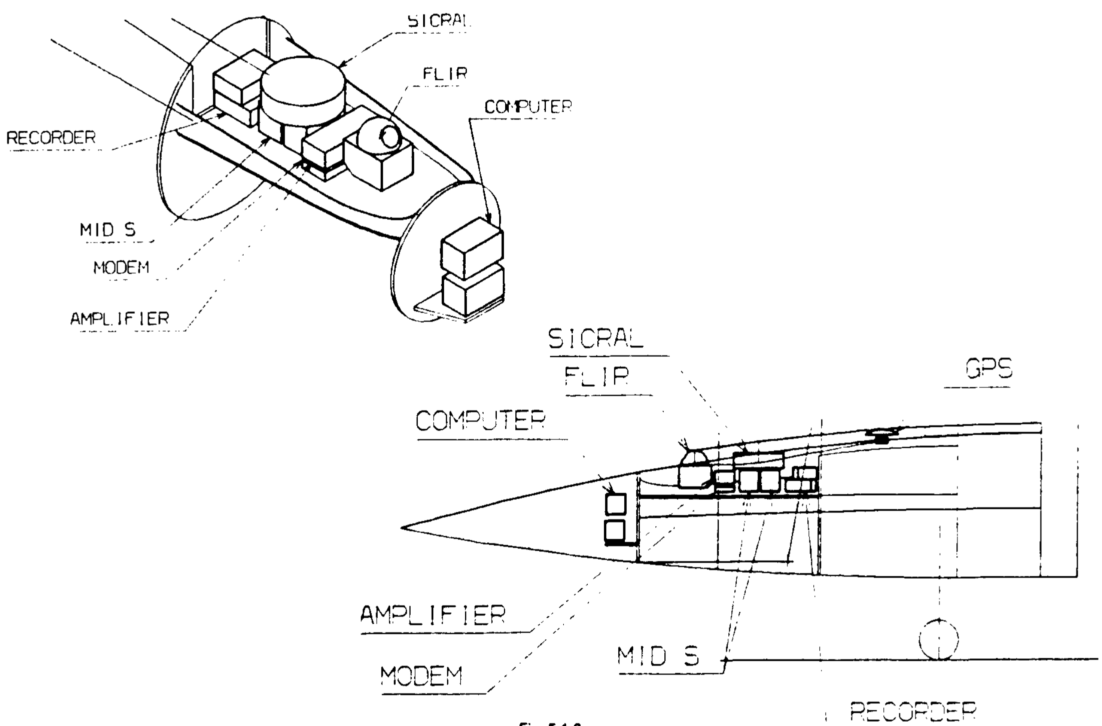


Fig. 5.1-3

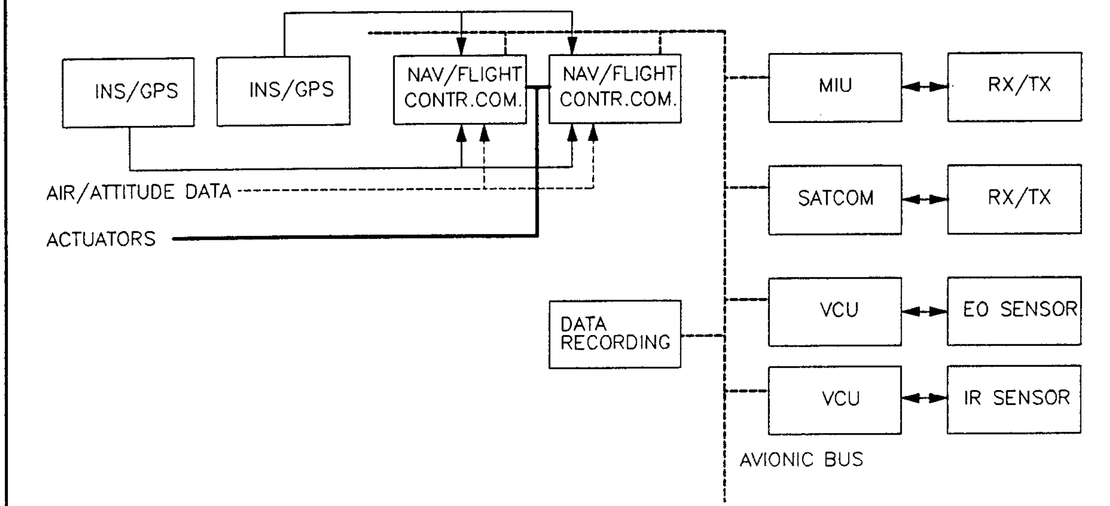


Fig. 5.1-4

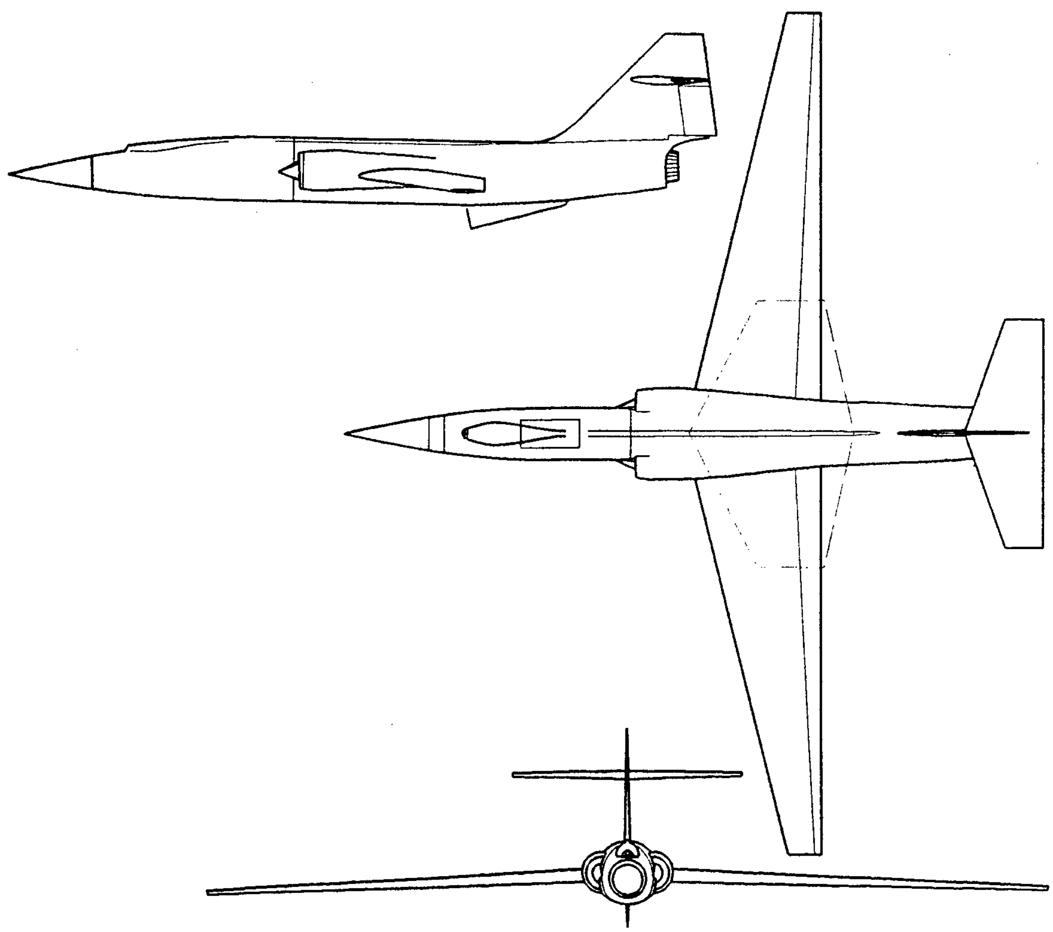


Fig. 5.2-1

The role of Unmanned Tactical Aircraft in the battlefield surveillance.

Régis Thevenot
Defense Systems Preliminary Design Department
High Altitude Long Endurance & UTA Systems design
Aerospatiale Espace & Defense
BP n° 2 - 78133 Les Mureaux Cedex
France

Antoine d'Audiffret
Program Manager
C3 and Intelligence Programs
Aerospatiale Espace & Defense
BP n° 2 - 78133 Les Mureaux Cedex
France

List of acronyms :

ACTD :	Advanced Concept Technology Demonstrator
ATO :	Air Task Order
CAOC :	Combined Air Operation Center
COMINT :	COMmmunication INTelligence
C4I :	Command, Control, Communication, Computer and Intelligence.
ELINT :	ELectronic INTelligence
IFF :	Identification Friend or Foe
JFC :	Joint Force Commander
MTI :	Moving Target Indicator
MTOW :	Maximum Take Off Weight
NBC :	Nuclear Bacteriologic and Chemical
SAR :	Synthetic Aperture Radar
SatCom :	Satellite Communication
SEAD :	Suppress Enemy Air Defense
SIGINT :	SIGnal INTelligence
STANAG :	STANdardization AGreement

1. SUMMARY

This paper deals with the role of Unmanned Tactical Aircraft (UTA) in tactical surveillance and support missions on a battlefield.

It addresses the main following points :

- A definition of what are the "UTA" addressed in this paper.
- An overview of the new battlefields and their influence in the surveillance and reconnaissance missions and architectures,
- A presentation of the environment where the UTA have to fly :
  - ⇨ atmospheric constraints,
  - ⇨ operational constraints,
  - ⇨ enemy constraints.
- A description of the various missions which could be performed. In particular, for reconnaissance and surveillance missions, some examples extracted from STANAG 3769 will be given and will demonstrate the ability of some classes of UTAs and sensors to perform some specific missions.
- An overview of some UTA proposed by Aerospatiale and some other companies with their main characteristics. This part will be focused on existing systems such as CL 289 (deployed in Bosnia), Medium Altitude vehicles and High Altitude Long Endurance concepts.

Presentation will end with the description of some Concepts of Operations for UTA systems on a Battlefield.

2. INTRODUCTION

The "end" of the "cold war" brought a lot of changes in the nature of the conflicts that NATO forces may have to cope with.

In a recent past (before 1989), battlefields were supposed to be made of a succession of lines rather well defined and concentrated on a rather small area.

Today battlefield surveillance becomes a new challenge for most of the forces as they have to realize missions on theaters where units are spread all over a large area. In such a configuration, potential threat may be very mobile all around some NATO or UN isolated positions.

This "new definition" of the battlefield makes necessary to have an efficient and continuous surveillance of wide areas in order to be able detect, in nearly real time, moves, changes in the enemy strategy and give alert when needed (situation awarness).

For such tactical missions UTA systems offer a very high level of capabilities.

Recent advances in :

- sensors (High resolution CCD cameras, Infrared sensors, SAR and MTI Radar, SIGINT, ...)
- communications (Satcom, High Rate Data Link, ...),
- jammers,
- aeronautical technologies (engines, light structures, ...)

make now available a large set of UTA and associated payloads. They are able to cover a lot of tactical surveillance reconnaissance or support needs of a modern army.

Paper presented at the AGARD MSP Symposium on "System Design Considerations for Unmanned Tactical Aircraft (UTA)", held in Athens, Greece, 7-9 October 1997, and published in CP-594.

However it is mandatory to notice that UTA systems are primary aerial vehicles which will have to cope with the enemy, the atmosphere, the air traffic and the air operations.

3. UTA ADDRESSED IN THIS PAPER

UTA addressed in this paper are mainly unmanned aerial systems designed for reconnaissance, surveillance et support missions.

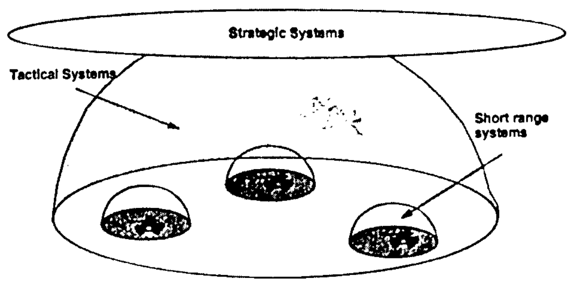
Three main categories of air vehicles and associated systems will be taken into account :

- fast, low altitude vehicles
- medium altitude vehicles
- high altitude vehicles

Concept of operations will only consider the case where these vehicles are directly used for the profit of tactical missions or for gathering information useful at the Joint Force Commander or Combined Air Operations Center levels.

The term UTA will be used for the overall system made with the air vehicle, the data links and the control ground segments.

Unmanned combat aircraft and short range automatic systems will not be addressed.



The various level of surveillance

4. THE NEW BATTLEFIELDS

In a recent past, forces of the various NATO countries were equipped and trained in order to cope with an East / West direct confrontation.

With such an assumption, battlefield was supposed to consist in a succession of rather "parallel" combat lines limited to a "small" area.

Recent operations demonstrated that in the next future such a configuration may still occur (Gulf War) but that very often NATO or UN forces will have to cope with new kinds of conflicts such as :

- guerrilla warefare,
- peace keeping,
- crises management, ...etc.

In all these cases, NATO or UN forces will be disseminated over a large area and will have to manage difficult tactical and operational situations.

Joint Force Commander will need three kinds of fundamental services :

- a good communication network,
- a good intelligence capability,
- a good set of supporting systems.

Such services might be widely based on unmanned tactical aircraft both for economical and safety reasons.

Moreover, to perform tactical missions, combat aircraft pilots will need more and more real time information which, again, may be gathered by unmanned systems.

4.1 Communication network

In a wide and hilly area such as Bosnia, implementation, operation and logistics around communication networks quickly became a very difficult task involving hundreds of operators and warfighters.

Such a situation may occur each time forces will have to be deployed, by small groups, over large areas. It will be even more challenging during the initial deployment phase and the final withdrawal phase.

As communication network is the "heart" of C4I systems "short term" solutions have been found in order to cope with these situations. Satcom, for instance, are more and more the mean that forces use to insure a kind of "minimum service".

In such a context the use of Long Endurance Unmanned Tactical Aircraft equipped with either tactical communication relay or digital broadcast system will provide a new capabilities to forces.

Recent studies just initiated in USA, UK or France demonstrate the potential interest of such a solution (Ref 1).

4.2 Intelligence on the battlefield.

To be able to manage the tactical situation, Joint Force Commander will have to know in nearly real time what are the enemy forces and positions. In addition he will need to get very quick information if any alert appears.

A lot of payloads are now available which allow intelligence services to collect the mandatory data :

- SAR and MTI Radar,
- COMINT systems,
- ELINT systems,
- NBC warning system, etc...

The main problems, as the payloads seem to be available, are :

- to insure the permanent surveillance of a large area,
- to collect the right data,
- to process in « real time » the data,
- to disseminate processed data through the C4I to the right user.

This supposes a high level of interoperability at each step of the chain.

Unmanned tactical aircraft may provide unique permanent surveillance capabilities. But for such a purpose, it may also become mandatory to make the UTA itself interoperable in order to allow a quick broadcasting of warning information for instance.

4.3 Support system

Military operations and more especially air operations are more and more supported by external systems such as :

- Communication relay,
- Target designators,
- Jammers, ...

Most of these hazardous missions are today carried out by manned systems.

A logical evolution would be to make these systems more and more efficient. A way to do it, is to allow them to go closer to the target (and the threat) by making them unmanned.

5. ENVIRONMENT ON THE BATTLEFIELD.

The number of actors on the battlefield is greater and greater. This implies that coordination and deconfliction are needed at all the levels of command.

UTA wil be one of these actors.

On the battlefield, all tactical unmanned aircraft will have to cope with three different kinds of constraints :

- atmospheric,
- operational,
- enemy.

In addition, if efficiency of the overall forces and survivability of some actors are based on the use of Unmanned Tactical Aircraft, these systems will have to be :

- available,
- reliable,
- survivable.

In these future mixed Manned / Unmanned missions UTA will be a key part of manned operations.

5.1 Atmospheric constraints

An aircraft operating in western Europe in all seasons may have to fly in very difficult conditions :

- wind,
- snow and ice,
- fog,
- thunders and lightening, ...etc

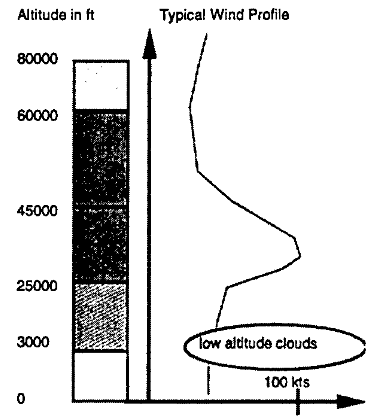
If the success of a combat mission (manned or unmanned) depends on the presence of an unmanned tactical aircraft, either for surveillance ; jamming or target designation, it is obvious that all these atmospheric constraints are to be taken into account from the initial design of the UTA.

In addition mission preparation systems and mission management system have to be able to take into account those constraints when defining the flight path.

If we only consider clouds and wind, two basic parameters which may affect the mission, it is to be noticed that :

- in Europe, wind may reach speed higher than 50 kts in all seasons in altitude,

- clouds often have a minimum ceiling lower than 1000 ft, especially in winter.



Typical wind and clouds distribution

This means that :

- a UTA flying at low speed (< 80 kts) may double its flight time to reach a way point if it meets "usual wind",

- a UTA equipped with an electropotical device or a laser device may have to be able to fly at an altitude lower than 1000 ft even in a hilly area...

Such elements may be important design drivers both for the UTA system and for the mission planning and preparation system.

5.2 Operational constraints

Main characteristic of an unmanned tactical aircraft in operation is that **it is an aircraft working for a customer.**

This means that these vehicles will have :

- to have the same kind of behavior than any other aircraft,

- to provide any time the service the customer is expecting.

To achieve such aims, UTA systems will have to cope with very strict operational constraints.

- They will be able to be integrated in the air operation system :
  - ⇨ ability to understand the ATO,
  - ⇨ ability to abide by the communication plan,
  - ⇨ ability to fly with other aircraft, ...

- They will be able to be integrated in the battlefield surveillance system :
  - ⇨ ability to understand the surveillance plan,
  - ⇨ ability to follow existing STANAGs for data collection, processing and dissemination, ...
  - ⇨ ability to interface with existing C4Is, ...

- They will create no additional work for the air control and coordination units :

  - ⇨ ability to follow air traffic control requests,
  - ⇨ implementation of IFF, BIFF ?
  - ⇨ implementation of voice transmitter, transponders, ... etc

- They will create no additional danger for troops overflown :

  - ⇨ high level of reliability.

5.3 Enemy constraints

Last but not least, UTA as a tactical system will have to fly over enemy positions to fulfill most of their missions.

Recent operations, such as Bosnia, gave the opportunity to test large and slow MAE tactical systems such as US Predator. But such a theater, with air supremacy insured, is may be not the only reference case to take into account for the future.

Anti aircraft guns (20 mm, 23 mm, 35 mm) or short range missiles (Stinger, Mistral, SA7, ...) may be very dangerous threat for UTA flying at low altitude and penetrating the enemy area.

These enemy constraints may lead to consider several kinds of UTA depending on the mission to be carried out.

As we already mentioned, survivability of the UTA system may become a fundamental design issue if UTA are used as supporting unit to manned systems.

6. THE MISSIONS

6.1 Reconnaissance missions

Main purpose of a reconnaissance mission is very often to make an identification of a well defined target.

STANAG 3769 (ref 2) allows us to get a better idea of the level of quality of the images collected which allow an identification of various kinds of targets :

Target	Minimum resolution in m
Bridges	1.5
Radar	0.3
Artillery gun	0.15
Vehicle	0.15
Fighter aircraft	0.15

Based on these values it is possible to evaluate on some classical electroptical payloads the maximum distance allowed to make a 50% identification.

With an IR gyro stabilized turret of the shelf and used on surveillance/reconnaissance UTA we have got the following minimum distances :

Target	Minimum distance for 50% identification
Bridges	3 km
Vehicle	2.2 km

With such a classical payload, the minimum distance for only 50 % identification is therefore less than 2 km...

In order to perform such a mission, UTA will have to fly lower than 6000 ft, even if there is no cloud. This means that most of the reconnaissance missions performed by UTA will be done in rather dangerous conditions.
Survivability of the UTA or ability to transmit in « real time » data gathered in all conditions will be of prime concern for the designer.

UTA able to perform this missions will have these basic qualities :

- survivable or real time transmission
- resistant to meteorological hazard
- low cost,

In addition it may be of high interest to get modular systems able to be accommodated with various payloads.

6.2 Tactical surveillance missions

Tactical surveillance missions can be splitted in two main activities :

- knowing and understanding of the enemy maneuvers,
- surveillance of a strategic point.

6.2.1 Surveillance of the maneuver

Ground and Airspace surveillance may become in the next decades the key of successful military operations.

UTA may provide data such as :

- SAR images,
- MTI locations,
- ELINT surveillance,
- COMINT surveillance,

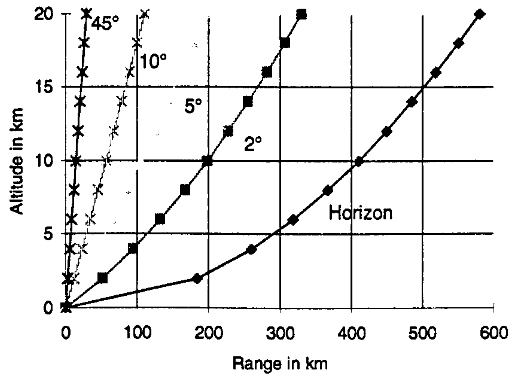
which will help Joint Force Commander and his staff to understand and manage the tactical situation.

To be efficient these missions require to fly for a long time at rather high altitude

For ground surveillance missions, the efficient range of detection is often far smaller than the theoretical geometrical range.

For Radar based ground surveillance for instance grazing angle may be considered as directly proportional to loitering altitude of the air vehicle.

For such a mission, gaining a factor 2 in altitude is roughly gaining a factor 2 on detection range.



Range as a function of grazing angle

For SIGINT missions effect of the altitude depends on the algorithm used to make the localization of the target. But altitude has a positive effect on the efficiency of the surveillance system.

Therefore surveillance of the maneuver needs high altitude systems. Permanent surveillance is in addition a strong asset and high altitude long endurance unmanned air vehicles could be a good solution.

For alert, real time is needed, but usually a 3 to 6 hours delay in processing and transmitting the data is acceptable.

During this surveillance phase, additional missions may be performed in order to prepare future operations such as ELINT data collection, COMINT data collection, mapping, ...etc.

UTA adapted to this mission are :

- able to fly very high altitude,
- long endurance,
- highly reliable,
- able to transport large payloads.

6.2.2 Surveillance of a strategic point

This mission is mainly a detection of activity on a pre-specified point.

It requires to be able to stay for a long time over the same point (without being shot down) and to be able to detect a predefined activity such as :

- troops movement,
- specific communications use,
- radar activity,
- aircraft take off...

Real time is often needed for these missions.

Main characteristics of the air vehicle are :

- long endurance,
- low observability,
- highly survivable,
- highly reliable.

6.3 Support missions

Unmanned systems may provide a very efficient support to manned operations, in particular by performing the most hazardous parts of the missions.

A good illustration of such a cooperation is a combined manned / unmanned mission in the scope of a SEAD mission (Suppressed Enemy Air Defense).

Manned aircraft are often penetrating the enemy area at high speed and low altitude. An automatic system could provide a efficient support by flying at higher altitude and making the SIGINT warning mission for the manned aircraft.

Other cooperation could be found with laser designation of a target for manned aircraft firing their weapons from a stand off position.

For all these missions, there is a very difficult compromise to find between three requirements :

- UTA has to make the most dangerous part of the mission and may be lost rather often,
- UTA are to stay affordable (low cost),
- UTA are to be reliable in their missions as the success of the manned mission may be based on its survivability.

As most of these missions are pre-planned missions defined in the ATO, and coordination between manned and unmanned system will be insured directly in the CAOC, this problem may be solved by using a new kind of UTA.

These UTA would have the following basic requirements :

- payload limited to a single tactical payload,
- highly survivable and reliable,
- able to fly the same speed than the combat aircraft,
- able to be operated simultaneously to manned aircraft.

7. SOME EXAMPLES OF UTA

The purpose of this chapter is not to make a catalog of all the UTAs able to perform the missions we described just before.

We will only illustrate with some examples developed by Aerospatiale or some other companies the various categories of UTAs that we pointed out and try to show their main characteristics for missions such as the ones described in this paper

7.1 Rapid air vehicles

First class to be described are vehicles specifically developed to survive in a rather hostile environment.

They are small and they fly at rather high speed (about Mach 0,8) at low altitude.

As they are not autonomous for take off and landing they often requires a rather heavy man power to maintain them operational.

They operational characteristics allow them to perform rather dangerous missions with a good chance of coming back.

7.1.1 The Firebee

The Firebee from Teledyne Ryan is the first automatic vehicle which have been used intensively in operations for reconnaissance purposes.

It performed about 3500 operational flights mainly over Vietnam from 1965 to 1975 (ref 3).

One of these vehicles "Tomcat" managed to perform 68 "combat" flights.

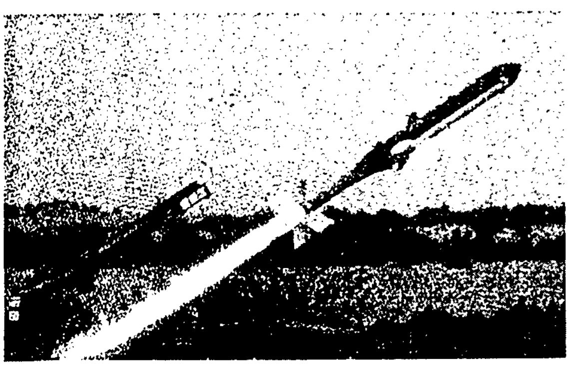
Firebee was mainly used in reconnaissance missions without data link.

7.1.2 The CL 289

The "CL289" has been initially developed by Canadair. A version developed with DASA/Dornier (for Germany) and Aerospatiale (for France) is now operational in Germany and France.

The "CL 289" has been used by France and Germany in Bosnia to verify Daytona treaty application .

This system demonstrated its capability of gathering very good photography even in rather difficult meteorological and operational conditions.



The CL 289 in the French Army

7.1.3 The BQM 145.

The "BQM 145" is a program leaded by Teledyne Ryan for the US Joint Program Office (JPO). The programme was known as « Medium Range UAV ».

This vehicle (Ref 3) either ground launched or air launched, 5.4 m long and 3.3 m span, able to fly up to Mach 0.8, is a good illustration of a rapid, penetrating reconnaissance UTA.

Program started in 1989 but has not been achieved due to budget restrictions... It was cancelled in November 1993, but some additionnal flight tests finally took place in 1996.

7.2 Medium Altitude Long Endurance

Medium altitude endurance systems are the new fashionable systems for tactical and operational intelligence.

They have the unique capability of maintaining a very long surveillance over a pre defined area.

They are operated as aircraft from a classical runway and a huge effort is made in order to make them interoperable with other UTA or with manned aircraft.

These vehicles are more and more numerous. Some of them, such as Predator has been used in operations in order to validate the concept.

7.2.1 TR 410

TR 410 from Teledyne Ryan is the first MAE vehicle which flown in 1988.

It has been designed on the basis of the know how of Teledyne Ryan but with no military specifications.

The aircraft (ref 3) is mainly designed to insure the robustness of the system :

- small span (less than 10 m),
- easy deployment (2 men),
- high speed (up to 140 kts),
- high wing loading (> 100 kg/m²).

and not only for endurance.

Its endurance is limited to about 17 h.

The TR 410 by Teledyne Ryan

7.2.2 The Predator

The "Predator" developed by General Atomics (USA) is the better known of the MAE systems.

This 14,4 m span UTA is the first ACTD carried out by DARPA. It illustrates the new generation of Unmanned Aerial systems designed for surveillance purpose. Its is able to loiter during about 40 h at 65 kts with a 200 kg payload.

It has been deployed for operational tests in Bosnia. These tests (Ref 4) demonstrated the advantages and drawbacks of such a solution.

Advantages are :

- High endurance,
- Large payload capacity,
- Real time interactive reconnaissance.

Drawbacks are :

- High sensitivity to meteorology,
- Airspace integration capabilities,
- Vulnerability at low altitude,
- Image quality for reconnaissance purpose.

The system is still in development and should be operational before the turn of the century.

7.2.3 The Heron

The Heron has been developed by IAI since 1992 (Ref 4).

It got a endurance record with more than 53 h without payload.

This system is very similar to the Predator in term of :

- payload mass,
- endurance,
- loitering speed.

7.3 High Altitude Long Endurance

High Altitude Long Endurance systems are well known now with all the communications made by the US about the Global Hawk and Dark Star programs.

But USA actually began working on this concept in the 60's with the Compass Arrow then the Compass Cope programs.

In the 80's, Boeing was chosen to lead the Condor Black Program. Condor is a very large aircraft (61 m of span, about 10 tons of MTOW). It performed a flight of 58 h up to 16.8 km of altitude in 1988.

With the new run up DARPA seems to give to the unmanned systems for military applications, this High Altitude Long Endurance concept seems to have a large chance of being one of the main tool for data collection over large areas in the next decades.

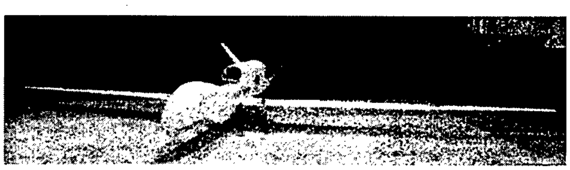
7.3.1 The Global Hawk

Global Hawk developed by Teledyne Ryan is a large aircraft of about 11 tons of MTOW and a 36 m span. It is able to fly up to 65000 ft during more than 40 hours.

First flight should occur by the fall of 1997.

The system has been mainly designed for real time surveillance of a large area from continental US :

- it has a large endurance (up to 40 h) at high altitude (65000 ft),
- it flies at high speed (about 650 km/h),
- it carries a large payload combining a powerful Satcom and a SAR radar and a EO/IR sensor.



The Global Hawk by Teledyne Ryan

7.3.2 The Sarohale

Aerospatiale has been working since 1993 on HALE concept. Vehicle which seems to be the best compromise for a European theater is about half the scale of the US Global Hawk.

- MTOW : 5.5 to 6 tons
- Span : about 25 m
- Payload mass : about 500 kg
- Ceiling : > 60000 ft
- Cruise speed : > 600 km/h

Technologies are mature enough to consider that such an airplane could be developed in about 3 years.

The SAROHALE by Aerospatiale

8 SOME CONCEPTS OF OPERATION

Main drivers to use UTA in operations are :

- their ability of being easily integrated in the air and intelligence operations,
- the Command and Control architecture which have to consider a man decision in most of the missions.

8.1 Integration in the operations

Its has been mentioned before that integration in the Air and Intelligence operations was one of the keys of success for unmanned aerial systems.

This integration has to be taken into account from the very preliminary design phase.

One of the main purposes of the Predator tests in Bosnia was the integration in air operations (Ref 4).

In addition, it seems more and more evident that for peacetime operations UTAs will have to be proven safe for the civilian population.

Therefore in a next future we can assume that UTA will have :

- to be "certified" in order to prove they safety,
- to be operated as a manned aircraft,
- to introduce no additional constraints for the air traffic control and coordination,
- to be interoperable within the existing C4I systems.

8.2 Command and Control architecture

Unmanned systems used in combination with manned systems will have to be able to abide by internal structures and rules of existing C4I.

For instance, a UTA used to support an air operations in order to make target designation will probably not be allowed to perform this mission fully automatically.

A man will have to be in the loop in order to validate the target and to avoid any collateral effect.

An other example could be a UTA in an ELINT mission supporting a SEAD mission. In such a case it could be of interest to use directly link 16 tactical data link to transmit a alert or a threat location.

Actually, such a direct use of a tactical data link by a UTA will not be seen before several decades as only validated tracks are supposed to be transmitted by this means. That is to say that the tracks have to be validated by an authorized person before any dissemination.

These two examples illustrate once more why **it is still mandatory to take into account the role of man as a key design parameter of unmanned systems.**

9 CONCLUSION

Technology will allow the emerging in the next decades of a large set of UTAs on the battlefield.

Some of them will be used for lethal missions, but in a first step most of them will probably be used for reconnaissance, surveillance, intelligence and support missions.
Their capabilities of gathering real time data and of operating in very dangerous areas and / or for very long periods will open a new age in data collection on the battlefield.

Used for the benefit of Joint Force Commander or in air operations, they will modify the way of conducting operations of the future.

They will become a key element of the future battlefield. Nevertheless a difficult compromise will have to be found between cost, efficiency and survivability.

10 REFERENCES

Ref 1 : Bruce D Nordwall. « UAVs may sub for Satcom on future Battlefield ». Aviation Week & Space Technology, April 28, 1997, page 52-55.

Ref 2 : Stanag 3769. « Minimum ground object size for imagery interpretation ».

Ref 3 : William Wagner, « Fireflies and other UAV's ». Aerofax inc. Publication.

Ref 4 : UV'97 conference. June 12/13, 1997 Paris.

HIGHLY MANEUVERABLE LETHAL VEHICLE (HMLV) CONCEPT

George M. Palfalvy
Dr. David K. Andes
Naval Air Warfare Center Weapons Division
China Lake, CA 93555-6100, U.S.A.
and
David Siegel
Office of Naval Research

SUMMARY

The paper presents interim results of a technology feasibility study of an unoccupied, armed, reusable, semi-autonomous air weapon system— the Highly Maneuverable Lethal Vehicle (HMLV). The HMLV concept that is currently being studied nominally has the following characteristics:

1. Acceleration capability greater than that of any manned aircraft
2. Sensors, sensor processing, automatic target recognition algorithms and reasoning/decision-making algorithms to allow it to operate almost completely autonomously
3. A variable-bandwidth, jam-resistant data-link to communicate images to an offboard controller
4. Lightweight, inexpensive, but precision guided and highly lethal, weaponry to prosecute air and surface targets
5. Airborne refueling capability

The study's goal is to examine applicable technologies and determine where they are lacking so that research funding can be properly focused.

Interim results indicate that

1. High-*g* airframes can be built (range and loiter capability for these airframes may be an issue).
2. Turbojet engines that can withstand the high-*g* environment can be built.
3. Sensor and signal-processing research is progressing at a rate that will produce sufficient capability in the near future.
4. The high-*g* capability of the HMLV, combined with a simple infrared countermeasure, will allow it to evade most threat missiles.
5. Advances in computational algorithms, including ATR, will be required.

INTRODUCTION

Unmanned aerial vehicles (UAVs) and remotely piloted vehicles (RPVs) have been fielded successfully for decades. The use of armed, unmanned platforms of various types has also been widely explored, but, to date, no really viable concept has been fielded. both for political and technological reasons.

Now, however, the technology to support very capable armed, unmanned, reusable, and semi-autonomous air vehicles (referred to as uninhabited combat air vehicles or UCAVs) is becoming available. The political acceptance of such vehicles is changing as well. The Navy, Air Force, Army, Defense Advanced Research Projects Agency (DARPA), National Aeronautics and Space Administration (NASA), and private industry are all investigating issues associated with the use of UCAVs to accomplish various war-fighting missions.

This paper presents the interim results of a current study of one UCAV variant called the Highly Maneuverable Lethal Vehicle (HMLV). The study is being conducted at the Naval Air Warfare Center Weapons Division (NAWCWPNS), China Lake, California, and is funded by the Office of Naval Research (Mr. Dave Siegel, ONR-351).

This study is an outgrowth of recognizing that, because of advanced foreign systems, it may become very difficult for the United States to develop aircraft and air-to-air missiles (AAMs) that maintain its superiority in air combat in the future. The state of the art in manned fighters combined with AAMs is reaching a high level for both sides. To maintain air superiority in the future, new approaches are needed.

Paper presented at the AGARD MSP Symposium on "System Design Considerations for Unmanned Tactical Aircraft (UTA)", held in Athens, Greece, 7-9 October 1997, and published in CP-594.

This recognition led to the consideration of an unmanned vehicle that exploits the fact that higher accelerations (and onset rates) can be achieved when no human is present. Once this approach was decided upon, the next questions became: "For what other missions and roles can such a vehicle be used and what are the characteristics that such a vehicle must have to perform the desired missions and roles?" This resulted in the current study.

The goal of the study is to determine the states of the arts of the various technology fields applicable to the concept and find out where they are lacking so that research funding can be properly focused in order to make the fielding of an HMLV feasible.

To reach this goal, the study is addressing HMLV missions and roles and the vehicle characteristics required to perform those missions and roles. Vehicle characteristics are being determined at a fairly high level. It would be inappropriate in this feasibility study to attempt to determine exactly any of the vehicle's characteristics or to attempt to specify an HMLV design.

The study considers only the technical feasibility of building and operating single vehicles and operating them independently of other assets. Therefore, some important issues associated with HMLV operations are not being addressed by the current study:

1. The use of offboard sensors. The capability of an HMLV would be greatly increased by using information obtained by offboard sensors, such as Joint Surveillance and Target Attack Radar System (JSTARS), satellites, and other UAVs, but this study addresses only the capability that can be attained with onboard sensors.
2. Mixed operations with manned aircraft. HMLV-type vehicles could play a significant role when used in conjunction with manned fighter or attack aircraft, but several issues must be resolved beforehand, such as safety and degree of control. This subject is beyond the scope of the current study.
3. The use of several HMLVs together. The authors believe that the real strength of HMLVs will be realized when they are operated in groups of several vehicles. One can envision the group exchanging sensor information and planning a coordinated attack, with each vehicle having thorough knowledge of what each group member is going to do and when. At that point the group truly becomes what might be called a distributed weapon system.

This paper reports on key areas that are the focus of the current study and reflects the fact that the current research concentrates on naval applications of the HMLV. However, it will be clear to the reader that these vehicles could play a significant role in missions conducted by other services. Finally, it must be emphasized that these results are of an interim nature in a quickly evolving field and are subject to modification.

GENERAL HMLV CHARACTERISTICS

To begin the study, it was necessary to generally define the type of vehicle on which to focus. To this end, a vehicle with the following general characteristics was envisioned:

1. Unmanned
2. Recoverable and reusable
3. Maneuver capability exceeding that of any manned aircraft and sufficient to evade advanced air intercept missiles
4. A level of autonomy similar to that used by manned fighter or attack aircraft being controlled by an air control aircraft (e.g., AWACS, E-2C) in that it accepts high-level commands but performs moment-by-moment decision making and actions independent of human intervention (Importantly, there is no joystick control.)
5. Sensors for inbound threat missile detection and targeting
6. Advanced computational capabilities to support onboard automatic target recognition (ATR) and decision-making algorithms that are capable of providing the required level of autonomy
7. A variable bandwidth data-link to communicate targeting information to and receive commands from an offboard commander (One important command that must be highly resistant to jamming and spoofing is the yes or no response by the commander to the vehicle's request to engage an object that it considers to be a target.)
8. Weaponry for fighter and attack roles (Note that the weaponry is probably required to be lightweight to be compatible with the vehicle's maneuverability requirements.)
9. Air-refuelable

These were determined to be the most important vehicle characteristics. As part of the study, these vehicle characteristics are being more accurately determined and others are being specified as necessary.

ADVANTAGES OF AN HMLV

If a vehicle with the previously listed characteristics can be fielded, it will have a revolutionary impact on the way future wars are fought. In particular, the following war-fighting advantages are readily apparent:

1. It would have an ability to evade most threat missiles using its ability to achieve high acceleration.
2. It could have a very high exchange ratio against manned aircraft using its ability to achieve high acceleration.
3. The loss of an HMLV would not result in the death of a pilot or any prisoners of war.
4. It can perform extended duration missions on the order of days or weeks by being air-refuelable and unmanned. This would allow it to loiter in an area and be ready to engage time-critical targets at a moment's notice.
5. It has consistent effectiveness, shorter reaction times, and the ability to handle a great deal of information without overload because of the sophisticated computational capability it possesses.

6. It may weigh and cost less than similar manned systems as a result of the lack of human support equipment such as an ejection seat, displays, etc.*

7. It would allow mission options that are not acceptable for manned systems such as one-way missions where the target is very deep in enemy territory and air-refueling is not a possibility or where the target is so heavily defended that it is unlikely that any attacker would be able to survive.

It is important to note that an HMLV with the general characteristics outlined will probably not be lightweight or inexpensive. On the contrary, for an HMLV to carry out certain naval war-fighting missions, it is likely that the vehicle will be very sophisticated, complex, and reasonably large and heavy, perhaps as large and heavy as a manned fighter or attack aircraft. An individual HMLV may cost as much as a manned fighter or attack aircraft.†

However, there are opportunities for significant cost savings associated with the operations, maintenance, and support of these types of vehicles. These savings are all related to the fact that the vehicles rarely need to be flown, except when conducting real missions in actual crisis situations. With manned aircraft, almost all of the flying hours are associated with training. With HMLVs, they can be stored in sealed containers within the ship until they are needed. There is no need to fly them to train pilots, because there are no pilots. Training of controllers can be performed almost exclusively by simulation.‡

Some of the reasons that cost savings are possible are

1. Fewer vehicles are lost or damaged. Vehicles will not be lost or damaged during training. Fewer spare vehicles will be required.

2. Less maintenance and repair is required. Maintenance and repair associated with training missions will be eliminated.

3. Carrier operations can be reduced. If HMLVs are deployed as part of a carrier airwing, then all of the ship's systems associated with airwing operations will be used less often because of the reduction in training flights, reducing the maintenance and repair costs of those ship systems.

4. Fewer maintenance personnel are required. Because the vehicles will be used, maintained, and repaired less often, the number of personnel needed to perform these tasks will be reduced.

5. Weaponry is less expensive. Because of its higher agility, the vehicle may have a high probability of survivable even in well defended areas. This could allow it to launch its weapons very close to its targets and, therefore, allow it to achieve high success rates even with relatively simple, very short-range and inexpensive weapons.

While there are many potential advantages to fielding an HMLV, there are also some significant challenges associated with trying to replace the capabilities that are lost when the weapon system has no onboard pilot or weapon systems operator. Most importantly, the crew's eyes and brains form a visual sensor and robust signal-processing and target-recognition system. The crew's brains also provide an advanced reasoning and decision-making capability that allows them to make generally reasonable decisions, even in situations that the crew may have never experienced before. Replacing these capabilities provided by the crew will test the state of the art in computer technology, including architecture, speed, memory, and algorithms.

MISSIONS AND ROLES

Missions, roles, and scenarios for use in analyzing HMLV conceptual design characteristics have been defined. Details are reported in Palfalvy[1]. A wide range of Navy missions and roles was examined to arrive at the primary roles to be used for the current study. Selection of the primary roles was based on need, potential for future shortfall, suitability to an HMLV-type vehicle, and suitability to single vehicle operations.

Based on these criteria, the following were selected as the primary roles to be examined as part of this study:

1. Air-to-air versus fighter-type aircraft
2. Attack of soft surface targets
3. Tactical ballistic missile (TBM) boost phase intercept
4. Forward fire control

Since Palfalvy[1] has been published, lethal suppression of enemy air defenses (SEAD) has been identified as another mission for which an HMLV is well suited. This mission will be included in the next revision of Palfalvy[1].

For each selected role, test case scenarios were defined. The test case scenarios that complement the primary roles delineate a set of scenarios that allow some of the most important characteristics of the HMLV, such as maneuver and loiter capability, to be tested in relative isolation. In developing the test case scenarios, reasonable—but not extremely advanced—threat capabilities were assumed.

---

* This may be offset by an increase in the amount of sensor and computer capability that will be required.

† It has been argued that an HMLV might be less expensive because it will not be required to be man-rated. The authors believe that it is not readily apparent that this would be the case, because the vehicle might be required to conduct operations in conjunction with and very near to manned aircraft. Furthermore, it may be required to land at airfields within heavily populated areas or on the decks of aircraft carriers.

‡ Some vehicles will need to be used when conducting exercises involving manned systems.

It is important to note that the goal of testing characteristics in isolation has necessarily led to scenarios that are very simple at the expense of operational realism. This was done intentionally to make it easier to determine the fundamental technical strengths and weaknesses of various HMLV designs and also to provide a crude filter for the candidates (i.e., if an HMLV design cannot be successful in the simple test case scenarios, then it cannot be successful in similar but more complicated and realistic scenarios). Later, when it is determined that certain HMLV designs can successfully perform their missions in the test case scenarios, then their performance in more realistic scenarios will be explored.

MANEUVERABILITY AND COUNTERMEASURES

Analysis was performed to determine the amount of maneuver capability required to evade air-to-air missiles and whether some form of countermeasure would also be required. High-fidelity simulations of several existing missiles were used to assist with this part of the study.

The analysis first focused on three aspects of the HMLV's maneuver: (1) maximum maneuver capability (maximum *g*s, measured in gravity units (*g*s)), (2) the time required to achieve the maximum *g*s (onset rate, measured in gravity units per second (*g*s/sec)), and (3) maneuver start time (measured in seconds before intercept).

The analysis showed that most current air-to-air missiles can be evaded, but advanced missiles with infrared (IR) seekers cannot be evaded without using maximum *g*s on the order of about 30 *g*s. However, even if the HMLV is capable of achieving 30 *g*s, the authors believe that missiles with sufficient maneuver capability to intercept the HMLV could be built. Such missiles probably do not exist now only because that level of capability has never been required. Also, it is probably less expensive and technologically demanding to build missiles that can achieve high-*g* levels than it is to build HMLVs that can evade them.

Because of this, the study considered the use of some form of countermeasure to supplement the HMLV's maneuver to attempt to defeat advanced missiles. A fairly simple IR countermeasure that would blind (i.e., deny information to) the missile seeker just before intercept was envisioned. It was postulated that if such a countermeasure could be constructed and if the employment of this countermeasure could be coordinated with the start of the HMLVs maneuver, then the vehicle could avoid the intercept.

Many computer runs were generated by varying the start time and the duration of the countermeasure along with the maximum *g*s, onset rate and maneuver start time. An advanced IR missile was used as the threat. The data generated by these runs indicated that if the HMLV could attain maximum *g*s of 15 to 20 *g*s, an onset rate of greater than 25 *g*s/sec, and the countermeasure was started about 0.2 second after the start of the maneuver and had a duration of about 0.3 second, then an advanced IR missile could be evaded. Furthermore, the length of the interval for successful evasion was about 0.6 second. Initiation of the necessary maneuver within this interval is possible if the HMLV can measure the range of the missile within about ±500 feet and the range rate of the missile within about ±400 f/s.[§]

AIRFRAME

An investigation aimed at obtaining rough size and weight estimates for an HMLV is under way. This investigation is being conducted with the assistance of the aircraft synthesis (ACSYNT) model. The following parameters were used as design constraints to initialize ACSYNT:

1. Instantaneous acceleration of 20 *g*s at 30 Kft and 0.95 Mach
2. Sustained acceleration of 6 *g*s at 30 Kft and 0.9 Mach
3. Avionics weighing 1000 lb and 1000 lb of weaponry
4. A mission consisting of 150 nmi flyout, 2 hours of loiter, 1.5 minutes of combat, and 150 nmi return to base[||]

With these constraints ACSYNT was exercised with each of three airframe types (conventional, canard, and delta). Both internal and external carriage of weaponry were considered. The conventional configuration was determined to be the best by a small margin. Internal carriage of weaponry was shown to be feasible. ACSYNT converged on an external carriage vehicle with a gross take-off weight of about 16,000 lb. The vehicle's length is 35 ft and its span is approximately 32 ft. It contains 5450 lb of fuel at takeoff.

Further analysis will be performed to determine if a mission with a longer duration and range can be accomplished by relaxing the instantaneous acceleration requirement while perhaps increasing the sustained acceleration requirement. Also, excursions will be conducted to see if more weaponry can be carried.

TURBOJET ENGINES

An investigation into the ability of turbojets to operate in environments of high accelerations has been conducted. The results of the investigation are based on an extensive literature search and numerous interviews with experts from most, if not all, of the major turbojet engine design and

---

§ There are other combinations of range and range rate measurement accuracies that allow the HMLV to successfully evade the missile.

|| This is a very minimal mission. The impact of extending the mission duration and range will be explored as part of this research.

manufacturing companies. Details of this investigation can be found in Burgner(2).

The investigation showed that current technology can support the design and construction of turbojet engines capable of operating in environments of up to 20 *gs* of acceleration. Strengthening of structures and bearings will be required. Any design will be required to consider that some components of the engine will probably undergo significant deformation during maneuvering. Also, extra emphasis will have to be placed on seal design to ensure that the seals function properly during maneuvers. However, it was concluded that the development of a new turbojet engine for an HMLV application would be no more costly than the development of an ordinary turbojet engine for a modern manned fighter aircraft.

SENSORS

The sensor suite is an important part of the HMLV. The sensors must detect, track, and estimate the time of arrival of missiles that threaten the vehicle. They must also be able to detect, acquire, and track air and surface targets (possibly in different types of weather conditions, a certain amount of obscuration, and darkness). The sensors must perform these tasks with enough accuracy and resolution to support ATR algorithms for preliminary target sorting and to support communication of candidate target images with an offboard commander for final target selection and a firing decision.

Research in this area is just beginning. It is envisioned that the vehicle will contain a medium resolution IR sensor with 4π steradian coverage and an effective range against tank-like targets of about 30 nmi. in clear weather. This sensor would be used for threat missile alert and passive detection of air and surface targets. It could be used to cue other high-resolution sensors that would help identify potential targets. Currently, IR, X-band, and millimeter wave (MMW) sensors are being considered for the high-resolution role. X-band and MMW are also being considered as longer range, weather-capable candidates for the detection and acquisition of potential targets.

A study is currently being undertaken to examine a MMW sensor with conformal antennas that promises very high resolution and good weather performance at reasonable ranges. System weight is currently estimated at about 400 pounds. Other results are too preliminary to report at this time.

SIGNAL PROCESSING

New computer architectures are being studied to determine their applicability to the problem of performing real-time signal processing and automatic target recognition on the large amounts of data that are generated by large sensor arrays. This research is being performed as part of a separate project sponsored by the Office of Naval Research.

That project is focusing on the use of massively parallel array processing chips and corticomorphic computing architectures to implement algorithms based on those used by the human eye and brain. Results to date look promising with computation rates on the order of 12,000 computations per pixel per frame for a 128 by 128 pixel array at a frame rate of 60 hertz. Many different types of algorithms have been explored, and the ability to detect and track moving targets in a cluttered background has been demonstrated.

Future research will focus on the details of implementing various detection and ATR schemes on high-density parallel hardware.

WARGAMING

With the assistance of Naval Reserve Unit NR NAWCWPNS 0170 stationed at Naval Air Station, Dallas, Texas, two tabletop wargames have been constructed and used to qualitatively examine the interplay between HMLV characteristics and operational issues.

The first wargame was based on a scenario that required an HMLV to engage and destroy a group of guided missile patrol boats (PTGs) that were threatening U.S. warships. This game showed that an HMLV equipped with only a gun is probably inadequate for this mission. This is mainly attributable to the fact that for the HMLV to engage the PTG with a gun, it must enter the lethal zone of the PTG's own defensive guns. In making a gun pass at a PTG that is countering with a high rate of fire gun, the probability that the HMLV will pass through the stream of bullets and be hit is unacceptably high, even if the HMLV is using a high-*g* evasive maneuver.

This resulted in examining a variation of the original scenario that considers an HMLV equipped with a 100-pound-class air-to-surface missile with a range that is sufficient to enable the HMLV to engage a PTG from beyond its gun range. The results of these games were much more satisfactory. It is estimated that such a missile using advances in warhead technology would yield very good results against targets such as PTGs.# Furthermore, the problem of battle damage assessment is greatly simplified by using a missile instead of a gun.

The second wargame, which is still under development, examines a scenario in which an HMLV patrols a region of suspected TBM operations. The goal is for the HMLV to locate and destroy TBM launchers in the region before they are able to launch their TBMs. Preliminary results indicate that an HMLV equipped with sensors and an associated ATR package capable of reliably detecting, tracking, and identifying TBM launchers at a range of about 15 nmi.

The current Hellfire is a 100-pound-class air-to-surface missile with considerable capability.

with a low error rate would allow the vehicle to cover a square region with a side length of at least 50 nmi.**

Details of the design and construction of the games and their associated assumptions, along with the qualitative results obtained by playing the games several times will be documented in upcoming reports.

CONCLUSIONS (AND CONCERNS)

The study of the characteristics required of an HMLV to perform certain Navy missions is still in progress. The concept in general appears to be sound. The state of the art of the technology in the areas of sensors, signal processing, automatic target recognition, control, communications, countermeasures, propulsion, and weaponry appears to be at or near the level of maturity required to support the fielding of an HMLV. Interim results yield the following general vehicle characteristics:

1. A maneuver capability of about 20 *g*s (instantaneous) with an onset rate of about 25 *g*s per second
2. A length of about 35 ft, a span of about 32 ft and a cross take-off weight of about 16000 lb
3. A payload of about 1000 pounds of advanced lightweight weaponry (note: an HMLV equipped with only a gun will not be able to carry out all postulated missions.)
4. Sensors capable of detecting inbound threat missiles at a range of about 2 to 3 nmi. with an accuracy of about ±500 feet in range and ±400 f/s in range rate
5. An IR countermeasure capable of denying information to a threat missile's seeker for a few tenths of a second

Concerns about the viability of the HMLV concept are presently centered around airframe issues. Using reasonable size and weight guidelines, current conceptual designs capable of meeting the desired acceleration requirements have limited range and loiter capability. Designs tend to be large (especially in wing area) for their weights and are unable to use all of their internal space as a result of the acceleration requirement. Trade-off studies of instantaneous and sustained acceleration capability, versus range, loiter, and payload will be pursued to attempt to understand all of the variables and find suitable designs that can achieve more useful mission ranges and loiter times.

Another area of concern is related to missions that require the HMLV to loiter at a slow speed over enemy territory. If, during the loiter, the vehicle is required to perform a high-*g* evasive maneuver, then there may not be sufficient warning for the vehicle to accelerate from its loiter speed to a speed at which it can perform a high-*g* maneuver.

** This result is dependent upon other assumptions built into the game, such as the number of TBM and surface-to-air missile (SAM) launchers in the region and the set-up time of the TBM launcher.

While the aforementioned concerns are valid, the study has not yet progressed sufficiently to conclude that these are real obstacles. It is more likely that as designs are refined and the problems are studied more thoroughly, solutions to these concerns will be found and highly capable, sophisticated HMLVs will someday be designed, built, and fielded.

REFERENCES

1. Naval Air Warfare Center Weapons Division. *Primary Roles and Test Case Scenario for the Study of the Highly Maneuverable Lethal Vehicle (U)*, by George M. Palfalvy. China Lake, Calif., NAWCWPNS, May 1995. (NAWCWPNS TM 7840, publication SECRET.)

2. ———. *The Ability of Turbine Engines to Operate With High Maneuver Loads*, by Gary R. Burgner. China Lake, Calif., NAWCWPNS, June 1996. (NAWCWPNS TM 7948, publication UNCLASSIFIED.)

The operational effectiveness of UCAVs in mobile target attack

B D Stewart

Centre for Defence Analysis
Defence Evaluation and Research Agency
Farnborough, Hampshire, GU14 0LX
UK

1 SUMMARY

This paper addresses a high-level approach to the analysis of uninhabited combat air vehicle (UCAV) effectiveness. The need for effectiveness analysis to take place in a range of realistic operational contexts is established, and the utility of effectiveness analysis is addressed. It is argued that it is necessary to take a 'system of systems' view in assessing UCAV effectiveness due to the diversity of impacts such systems will have on military operations. Relationships between some areas of UCAV performance, and their impacts on UCAV effectiveness, are presented as examples of the complexity of UCAV operations and to demonstrate the need for effectiveness analysis to assist in system definition.

2 INTRODUCTION

Recent years have seen an explosion in the attention paid to uninhabited air vehicle (UAV) concepts and technologies. Three main drivers can be identified for this explosion:

- improvements in technology;
- the escalating cost of manned aircraft coupled with a general reduction in military budgets;
- the changing political environment.

Through recent advances in the fields of sensors, communications, and computing technology, UAVs offer the potential of high levels of military effectiveness at low levels of cost. At the same time, UAVs offer interesting challenges to scientists and engineers, allowing them to push back the boundaries of contemporary aviation technology. Finally, with the end of the cold war, and the establishment of 'the new world disorder', the relative importance of 'operations other than war' has increased, bringing with it a range of problems that have not been widely addressed in the past.

Against this background, it is necessary for political and military decision makers to be able to strike an objective balance between conventional inhabited air vehicles and the revolutionary possibilities offered by new UAVs. This balance must be struck so as to provide optimal military cost-effectiveness across the range of operational situations that may occur. Cost-effectiveness analysis of potential systems is used to inform decision making within the procurement process (e.g. the UK's combined operational effectiveness and investment appraisal (COEIA)).

In addition to its utility in informing procurement decisions, cost-effectiveness analysis can also be used to explore system trade-offs and the prioritisation of system capabilities against defined operational requirements. This allows for the early focusing of resources on those elements of system capability that offer the greatest potential for pay-off in terms of military effectiveness. It is often the case that the true drivers of military effectiveness are not obvious. Cost-effectiveness analysis can also be used to investigate military concepts of operation, and technology balance of investment.

This paper has been prepared with the specific focus of offensive operations against mobile targets. While this is often seen as a problem of 'sensor to shooter' connectivity, this ignores many other problem areas such as target detection, target identification, avoidance of collateral damage, and the integration of attack assets with other air operations. The introduction of UAV concepts into this role provides many new challenges. UAV operations against mobile targets need to be evaluated in the light of all of their potential impacts on the problem, and not only those which get the most attention in the press.

3 DEFINITION OF TERMS

Several phrases used in this paper could be considered 'buzz-words' and therefore need more formal definition. The definitions given are for the purposes of this paper, and should not be considered as being generally 'definitive'.

3.1 UCAV

Paper presented at the AGARD MSP Symposium on "System Design Considerations for Unmanned Tactical Aircraft (UTA)", held in Athens, Greece, 7-9 October 1997, and published in CP-594.

An uninhabited combat air vehicle. This is an uninhabited air vehicle that functions as part of a combat system (that is, one whose end goal is the delivery of weapons to targets). This definition means that a UAV carrying a sensor system that provides targeting data to a weapons platform is considered a UCAV. This definition is used to emphasise the holistic view that should be taken in the analysis of UCAV mobile target attack.

3.2 Effectiveness

Effectiveness is defined as being the level of impact of the performance of a system on a defined operational context, and is measured in terms of defined military goals (e.g. the destruction of tanks) rather than physical values (e.g. penetration of armour in mm). That is, effectiveness is the level of 'military worth' of the system.

Effectiveness can be viewed as arising from the interaction between technology, tactics and environment.

3.3 Mobile target

A target which is not fixed in space. Since virtually any target can be moved in some timescale this means that a time threshold must be set. For the purposes of this paper a mobile target will be considered to be one which can relocate within the timescale of the operation of an Air Tasking Order (ATO).

It should be noted that a mobile target is not necessarily a moving target. The target may well be stationary for significant periods of time (e.g. mobile strategic surface-to-air missile batteries).

4 OPERATIONAL CONTEXTS

UK defence doctrine (as a consequence of wider national policy) recognises that the UK armed forces may be required to act in many different roles and geographic locations. This gives rise to a wide range of potential environments in which military systems may be required to operate (the word environment is taken to include the military context of an operation as well as its geographic location). It is important to understand that the impact of a particular military system (and hence its effectiveness) will vary depending upon the environment in which it is deployed. For example, arctic survival clothing is highly effective in arctic conditions, but if deployed in the Persian Gulf region during summer, it would not only be completely useless, but actually counter-productive.

For this reason it is necessary to postulate a number of operational contexts (or 'scenarios') in which the capabilities of systems can be evaluated. This ensures that the system or systems procured can deliver an acceptable degree of military effectiveness across the range of contexts that might be required by national policy.

In postulating scenarios it is necessary to address the range of scenario-driven factors that will significantly impact on the problem at hand These factors are termed scenario characteristics. For many problems there are likely to be a large number of such characteristics, all of which can take multiple values. In theory this requires a large number of scenarios to fully analyse the impact of differing operational contexts on system effectiveness. There is a balance to be struck between completeness and cost. DERA has developed a method for scenario selection based on coverage of relevant scenario characteristics and their distinct values, so as to get the optimum level of problem coverage for the least number of scenarios.

An example of a scenario characteristic might be the 'level' of an operation. This might range from general war, involving the full resources of a nation or nations, to peace support operations using perhaps only a handful of personnel. This characteristic would significantly impact on the range of possible military goals in the scenarios selected. In addition, where similar military goals might exist in different levels of operations (e.g. suppression of enemy air defences, or suppression of ground force movements), the balance of importance between them may alter. Furthermore the methods that could be used in different operations may also differ (e.g. jamming as opposed to destruction of air defence sites).

Some scenario characteristics of particular relevance to UCAV operations and technology, insofar as they may impact on the desirability of using a UCAV as opposed to an inhabited combat air vehicle, or a particular UCAV solution as opposed to another (e.g. autonomous operation versus a remotely piloted vehicle (RPV)) are:

> rules of engagement - these may have a strong influence on the permitted degree of autonomy of a UCAV system;
>
> sophistication and density of enemy air defences - these are of particular relevance to the issue of risk to aircrew (when comparing inhabited with uninhabited air vehicles);
>
> size of geographic area of interest - can impact on required levels of air platform endurance and range (which is relevant to inhabited versus

uninhabited operations), and communications infrastructure requirements based on line-of-sight restrictions (which is particularly relevant when considering the degree of autonomy of UCAV systems).

5 EFFECTIVENESS ANALYSIS

As defined earlier, military effectiveness relates to the impact of systems in realistic operational contexts. Taking the 'system level view' in measuring effectiveness is widely accepted as being necessary in most situations. However there is often a question of how far 'the system' actually extends. Furthermore, most military systems depend on other systems to provide them with the environment in which they can operate, e.g. the most potent air superiority fighter in the world is not effective without the support systems that get it airborne (fuel delivery, maintenance, command and control etc). For the attainment for military goals in realistic contexts, it is almost always the case that many systems have to work together. Thus military effectiveness is often not a system-level attribute, but arises from the interactions between many systems. This is the basis for taking a system of systems level view of military effectiveness.

In practice, this is not always done. This is justifiable when the impact of a particular system type is well understood, and where the functions of the supporting systems in the system of systems do not substantially alter as a consequence of the system under study. However, UCAVs as a concept are still immature and it is widely felt that they will have multiple impacts in many areas of military operations. This would suggest that the system of systems level view is the appropriate one to take.

But what specifically is meant by the effectiveness of the system of systems? Effectiveness is measured in terms of parameters known as Measures of Effectiveness (MoEs). These MoEs vary depending on the nature of the system being studied and the purposes for which it is intended. However it is often the case in combat modelling that military effectiveness is measured in terms of some combination of the following three factors:

targets destroyed (or targets suppressed);

own force losses;

collateral damage inflicted.

The first two factors reflect traditional approaches to the measurement of military effectiveness (e.g. Lanchesterian type analysis). The third factor has risen in importance in recent years, and in some types of operation may actually be of greater importance than the other two (e.g. peace support operations). Other measures are also used, but in almost all cases are constructed in some fashion from those listed above (a measure of the position of the forward line of own troops (FLOT) against time will often depend on the remaining enemy strength at that time related to that of friendly forces).

Political effectiveness, or the impact of military effectiveness on the political context of a particular operation, is much harder to quantify. It may be that a high degree of military effectiveness in terms of targets destroyed for example, may actually be politically counter-productive. For this reason effectiveness analysis often steers clear of these muddy waters. Nevertheless DERA is sometimes required to generate non-traditional measures for situations such as peace-support operations.

In situations where procurement or investment advice is being generated, system costs must also be taken into account. In procurement support, cost-effectiveness analysis is required as effectiveness analysis alone can lead to the 'gold-plated silver bullet' solution. UCAV cost analysis is of as much importance as effectiveness analysis. It is however beyond the scope of this paper to consider cost further.

The approach used to address the question of UCAV effectiveness in the attack of mobile targets is first to consider the problem from a generic viewpoint, i.e. not specifically as a UCAV problem. After this, the specific effects of UCAV operations on the generic problem can be considered. The effectiveness analysis is carried out by considering the measures of effectiveness, the factors that impact upon them, how those factors interact, which factors impact on them, how they interact and so on. This leads to the production of a 'structure' which illustrates the scope of the problem.

The structure developed can be used in a number of ways. For example, it can be converted into a 'model' through the use of a systems dynamics type approach, or it could be used as the basis for a specification for a conventional computer simulation (or more likely a series of simulations) and how the outputs of those simulations should be integrated. A useful initial output from such an activity is the ability to use such structures to form the basis for discussion, to point out interactions which may otherwise be missed, and to identify areas where feedback may occur (positive feedback between factors may identify potentially useful synergies whereas negative feedback may suggest areas where variations in performance may have little impact).

6 UCAV EFFECTIVENESS

6.1 GENERAL DISCUSSION

So far this paper has addressed why UCAVs should be considered as part of a system of systems, and why effectiveness analysis is a vital tool in system development. One element of this is the comparison of conflicting requirements, or concepts of operation e.g. comparing the trade between expensive sophisticated defensive aids to allow high altitude operation, versus the performance penalties due to low altitude operation without those aids, for example in a penetrating reconnaissance system.

Having followed the 'structural' approach suggested above we can begin to pull out areas of particular relevance to UCAV operations. Not surprisingly these are areas which are already known of and are being worked upon, e.g. the issue of automatic target recognition, which if reliable could lead to autonomous UCAVs with good enough target identification capabilities to be allowed to attack those targets without human intervention. What are not always apparent are the multiple impacts that some factors can have on system effectiveness, e.g. 'Risk to crew'. The main impact of this factor is often seen as being on weapon types used (stand-off or short ranged). However, this also impacts on the routeing options useable and therefore the system's transit time to its weapon release point, therefore the timeliness of its attack, therefore the required trade-off between target location accuracy and the timeliness of the target location data, the required sensor coverage and quality, the numbers of platforms required and so on. Some factors are likely to have non-obvious, non-linear impacts on system effectiveness due to having complex interactions with other factors, and due to the potential for feedback between them. The ability to identify these interactions explicitly is a strength of this 'structural' approach to the analysis of UCAV system effectiveness.

6.2 SYSTEM AUTONOMY

One issue which is often discussed in the UCAV arena is system autonomy for attack platforms. In essence, the main problem that is perceived is whether an autonomous system would have the capability to detect and identify its targets without human intervention, and particularly in low-intensity conflict settings, whether it would be able to reject false targets such as civilian traffic. The degree of human/machine intelligence of the system, combined with the timeliness and accuracy of the targeting data with which it is provided, contribute to the correct identification of targets. This combines with several other factors to drive target destruction, the level of collateral damage inflicted, and hence system effectiveness. Another factor impacting on this area is the location of the human/machine intelligence. This issue of 'where is the intelligence in the system?' is one that is likely to be critical for future UCAV systems, in particular in the attack of mobile targets.

In attacking mobile targets there will be a premium in correctly locating targets in a background environment where both target position and the nature of the environment may have changed since the last targeting update. The location of the intelligence in the system is likely to be an effectiveness driver. An inhabited combat air vehicle will have human decision making capabilities on the scene, but will suffer the limitations imposed by the requirement to carry crew. Alternatively a remotely piloted vehicle will have human decision making capabilities but will rely upon communication links to allow them to be used. Those communication links could be jammed, malfunction, or be limited by line-of-sight, or satellite usage restrictions. Further they could make the system more vulnerable to detection and hence less survivable. A fully autonomous UCAV would have no need for human decision making, thus it could enjoy all of the benefits of being designed without the need for a crew, and at the same time not suffer from the limitations of requiring the communications support that characterises the RPV. However, how reliable would the autonomous system be, and given its limitations (if any), in what circumstances and therefore how often could it be used? These issues can be addressed through effectiveness analysis, in particular the mix of such capabilities which may be required.

6.3 SURVEILLANCE, TARGET ACQUISITION AND RECONNAISSANCE (STAR)

An area in which UCAVs are seen as being of particular use is in providing STAR coverage. In the main this is due to the potential for very long endurance, allowing for substantial coverage with limited assets, and the lack of risk to crew (which has already been discussed). Unfortunately there is a tendency to overstate the impact of such systems, with images of constellations of UAVs freely wandering the skies providing instant intelligence on any target of interest in enemy territory being not uncommon in the open literature. It would be very dangerous to design a mobile target attack system based purely on such an image. Consideration must be given to countermeasures which could be applied by an enemy to protect his assets, particularly those which could be considered to be 'high value' e.g. tactical ballistic missiles, mobile SAMs, mobile command and control.

One countermeasure that could be employed would be to operate high value mobile assets in areas with substantial surface-to-air missile defences as well as radar sites, electronic intelligence (ELINT) systems etc. Aggressive fighter sweeps over such areas could also be envisaged with radar, infra-red, radio frequency and optical sensors all playing a role in the detection of surveillance platforms. Considering the ballistic missile target, by the time such defences could be suppressed to a level allowing effective operation of friendly sensor assets, it may be the case that the enemy may have already had sufficient time to launch most of his stocks. Of course, the level of effort required by the enemy to mount such a defence may either be beyond him, or may adversely impact on his other operations. In this second case it could be argued that the friendly system was still effective through the threat of its use requiring the enemy to act in a sub-optimal manner. The evaluation of enemy countermeasures and their effects both on the UCAV system in question, and the wider operational context as a whole, is an area in which effectiveness analysis can provide value to decision makers and system designers.

7 CONCLUSION

The impact of UCAVs on military operations will be far more wide ranging than would be suggested by simply considering them to be 'aircraft without pilots'. Because their impacts will be so wide ranging it is necessary for rigorous cost-effectiveness analysis of UCAV systems in a wide range of operational contexts to be carried out. This will be fundamental to the successful integration of UCAVs into military operations in such a way as to meet future national objectives. However, cost-effectiveness analysis should not be seen as simply an aid to procurement decision making. It should be integrated into the design process of future UCAV systems as a means of focusing effort on key system effectiveness drivers, and of avoiding unnecessary or inappropriate effort in areas of marginal impact on system cost-effectiveness.

8 CLASSIFICATION

UNCLASSIFIED

This paper represents the views of the author, it does not necessarily represent the official views of the Defence Evaluation and Research Agency nor the UK MOD.

DESIGN CONSIDERATIONS FOR FUTURE UNINHABITED COMBAT AIR VEHICLES

Dr. Armand J. Chaput
Company Specialist
Lockheed Martin Tactical Aircraft Systems
P.O. Box 748, Mail Zone 2458
Fort Worth, Texas 76101

SUMMARY

A potential shortfall in U.S. tactical aircraft inventories required to meet future national and international defense contingency requirements early in the next century is projected to materialize some time during the period 2005-2015. The Uninhabited Combat Air Vehicle (UCAV) system concept has potential to help resolve the projected inventory shortfall. Lockheed Martin Tactical Aircraft Systems (LMTAS) studies have identified a number of potential roles and missions in which the UCAV should be both cost and operationally effective. The UCAV concept, however, is unproven and needs system concept technology development, evaluation and demonstration if it is to be considered a viable candidate to meet the projected shortfall. A near-term development program that includes overall system simulation, evaluation and demonstration in combination with configuration specific advanced technology development (ATD) will ensure that defense planners have a viable alternative ready for decision by the time the projected shortfall materializes.

NOTATION

AFRL - Air Force Research Laboratory
AFTI - Advanced Fighter Technology Integration
ATD - Advanced Technology demonstration
AWACS - Airborne Warning and Control System
BDA - Bomb Damage Assessment
BVR - Beyond Visual Range
CAP - Combat Air Patrol
CAS - Close Air Support
CONOPS - Concepts of Operation
COTS - Commercial Off-the-shelf
C3I - Command Control Communication and Intelligence
DoD - Department of Defense
DTC - Data Transfer Cartridge
FATE - Future Aircraft Technology Enhancements
IPT - Integrated Product Team
JSTARS - Joint Surveillance Target Attack Radar System
LCC - Life Cycle Cost
LED - Long Endurance Derivative
LMSW - Lockheed Martin Skunk Works
LMTAS - Lockheed Martin Tactical Aircraft Systems
MITL - Man-in-the-loop
NRT - Non Real Time
O&S - Operations and Support
STOVL - Short takeoff, Vertical Landing
R&D - Research and Development
UAV - Unmanned Aerial Vehicle
UCAV - Uninhabited Combat Air Vehicle
URAV - Uninhabited Reconnaissance Air Vehicle
USAF - U. S. Air Force
VISTA - Variable In-flight Stability Technology Augmentation
WVR - Within Visual Range

1. INTRODUCTION

It would not be presumptuous to assume that today every military fighter design organization in the world is trying to determine the future scope and direction of their customers' product needs in an attempt to position themselves to meet 21st century business opportunities. Certainly this is the case at LMTAS where a number of multi-discipline integrated product teams (IPTs) are looking at a range of new product ideas to meet known or projected theater air combat needs. Included among them is the UCAV IPT which has been conducting Independent and Contracted Research and Development (R&D) in this area since 1994.

LMTAS involvement in UCAV resulted from internal studies which identified the general concept as a likely inclusion in future force structures. In October 1995 our IPT collaborated and presented an AGARD paper entitled, "Unmanned Tactical Aircraft - A Lockheed Martin Perspective" through our Skunk Works (LMSW) colleague, Dr. Lee Nicolai (Ref 1). It laid out our assessment of the key drivers behind what is now called the UCAV concept - political aversion to crew loss or capture and defense cost constraints. Risk of loss or capture required little explanation. Cost related issues were not quite as straight forward. Many assumed that the primary cost advantage of unmanned vehicles would derive from removal of man-rated systems and requirements. We concluded, however, these savings were small in comparison to the real cost driver - a potential order of magnitude reduction in peacetime operations and support (O&S) costs.

On modern systems like the F-16, O&S costs represent about 40% of the total life cycle cost (LCC). An order of magnitude reduction in O&S cost, therefore, could reduce overall LCC by about one-third. The cost savings derive from a fundamental change in how UCAV operators would maintain combat proficiency during peacetime in comparison to their manned fighter counterparts. UCAV operators would rely primarily on simulation for proficiency maintenance and only fly their vehicles when required for exercises and/or actual combat. In comparison, typical manned fighter proficiency flight operations represent the vast majority of all squadron hours flown. Therefore, the UCAV concept of operation alone showed potential for significantly reducing annual flight hour requirements and all of the support personnel and consumables that go with them. There also would be a commensurate drop in wear and tear on the aircraft themselves.

Paper presented at the AGARD MSP Symposium on "System Design Considerations for Unmanned Tactical Aircraft (UTA)", held in Athens, Greece, 7-9 October 1997, and published in CP-594.

Since that initial AGARD paper, a number of studies have been conducted to evaluate claimed cost and effectiveness benefits. In general, these studies have supported our conclusions, although many considered our projections to be optimistic. We, however, have found no flaws in our calculations or assumptions and believe that the cost savings projected for UCAV remains valid. In the meantime, we have gained a better understanding of the advantages, disadvantages, capabilities, limitations, technical drivers and risks associated with the overall concept. On the second anniversary of our first paper, we are once again pleased to share the results of our studies with our colleagues from AGARD.

1.1 Aircrew Risk

Many might believe that the impetus for the recent interest in uninhabited aircraft is a relatively recent aversion to crew loss or capture, driving us to want to position our aircrews well out of harms way. In reality positioning for survivability has always been our objective, whether it be through the use of altitude to avoid ground fire or through improved performance, allowing our fighters to position themselves behind, not in front of, an opponent's guns. As time, technology and tactics progressed, however, we found ourselves either moving our air crews further and further back from threat or relying on sophisticated technologies and tactics to allow them to survive at closer ranges. Even with sophisticated technology and tactics, however, standoff weapons now are the preferred delivery option. The problem is that as the standoff range required for survivability increases and/or required weapon guidance systems become more complex, the cost of destroying the target escalates accordingly. Some, in fact, might argue that at some point, it is cheaper to standoff completely and use cruise or ballistic missiles instead.

1.2 Options

The cost argument for and against the missile option is shown in Figure 1. Here a simple cost per pound of delivered payload metric is used to compare various ways of attacking targets, both air-to-ground or air-to-air.[1] The figure shows that on the basis of cost per pound of payload delivered, using a cruise missile to put a given payload on target is about two orders of magnitude more

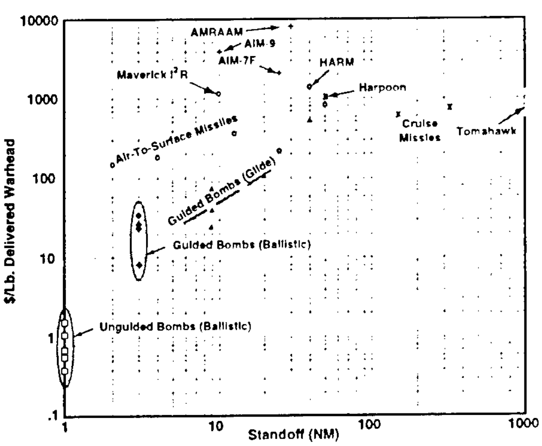


Figure 1. Weapon Delivery Cost Drivers

[1]This metric was chosen for purposes of simplicity. It intentionally ignores effectiveness and other contentious differences.

expensive than using a fighter-launched precision-guided bomb. The fighter advocate would argue that he has a cost advantage because most of his system is reusable while the cruise missile and most of its expensive parts (propulsion, guidance, etc.) are destroyed with the target. The cruise missile advocate, on the other hand, would argue that if the fighter has to rely on standoff for survival, beyond about 50 NM (90 Km) a fighter has little cost advantage, particularly as the unit cost of cruise missiles continues to drop while the unit costs of low-rate production fighters have been increasing. The cruise missile advocate would also argue that as the complexity of the fighter delivered standoff weapon guidance system increases, the cost advantages dwindle even more quickly.

Our assessment is that both sides are right. If a fighter can penetrate and survive at relatively short standoff distances, it will be the lowest cost alternative but only if its higher acquisition and support cost can be amortized over enough targets and missions. If, however, significant standoff is required to achieve fighter survivability and higher fighter cost cannot be spread over enough targets, a cruise missile may be the least expensive approach. When crew loss or capture is itself not an option, today's only viable option is a cruise missile. With UCAV development, however, there would be another option that has potential to be both effective and lower cost than either a fighter delivered PGM or a cruise missile.

On the advantage side, compared to a cruise missile a UCAV can be routed around pop-up threats. Compared to a fighter it can be designed for higher "g" loads and more aggressive maneuvers. UCAV will also have disadvantages though. For example, it will almost certainly be larger than a cruise missile and, at least for the near term, probably will be vulnerable to manned fighters within visual range (WVR). Beyond visual range (BVR), there is no technical reason to believe that a UCAV could not hold its own against a manned fighter. In the longer term, it is conceivable that technology could even make it formidable within visual range (WVR). All of these options, however, are unsubstantiated assertions. UCAV is a concept for which there is currently little or no data, technical or operational, that would allow it to compete as a viable military alternative to contemporary cruise missiles and fighters, much less an effective alternative to placing air crew at risk of loss or capture in a situation when victory in the air or ground must be assured. The only way that UCAV could be considered a viable option is to subject the concept to in-depth evaluation, including technical and operational feasibility, cost, risk and demonstration. Then and only then should the concept be considered anything more than an attractive possibility.

1.3 Demonstration Requirements

Most of the issues associated with the UCAV concept are amenable to evaluation and resolution through the ATD process. Most of the studies referenced in this paper recommended the ATD approach. These recommendations have been taken seriously and programs are being formulated. For example, the U.S. Air Force Research Laboratory (AFRL) has initiated its Future Aircraft Technology Enhancements (FATE) program that proposes to evaluate a number of issues common to both manned fighters and UCAV. This could culminate in development of an innovative new un-

manned vehicle demonstrator. Some issues do not require new vehicle development to evaluate and demonstrate, however. For example, datalink connectivity and bandwidth availability, manned unmanned interoperability, deployment, and aerial refueling essentially are vehicle independent issues. And while some CONOPS issues are vehicle dependent, many are not and do not require new vehicle development to evaluate and/or demonstrate. In fact, some aspects of UCAV CONOPS development may be incompatible with new vehicle development, for example, CONOPS evaluations that require significant numbers of aircraft to evaluate. Therefore, a number of studies such as the USAF SAB have recommended that data link equipped manned fighters be used as surrogate UCAVs for demonstration and/or evaluation purposes. For reasons of safety and operational flexibility, these vehicles would remain manned and have on board safety pilots in the event of emergencies or equipment failure. Lockheed Martin believes that this approach, whether based on manned fighters, new demonstrators or modified versions of existing Unmanned Aerial Vehicles (UAVs) or drones, is a key element in overall technical and operational risk reduction for the overall UCAV system concept.

2. FORCE STRUCTURE ISSUES

Most of the issues discussed in this paper are applicable to all defense forces, U.S. and Allied. For brevity, however, this paper focuses on the U. S. Air Force (USAF). We will leave it to the reader to extrapolate the issues and potential solutions to their own particular service and/or national needs.

Simply stated, the problem facing the USAF (and every other service) is how to meet a range of changing defense needs world wide with shrinking budgets and fewer people. The fundamental issue is one of force size and required capability. For example, the latest Quadrennial Defense Review established a firm requirement for 20 USAF fighter wings. The basis for conclusion was a projected requirement to conduct 2 near simultaneous major theater wars. Some critics argue that this is an unreasonable projection and that perhaps as few as 15 wings might suffice. An internal LMTAS study, however, shows that 20 wings is a minimum requirement to meet even peacetime requirements.

The LMTAS study addressed the types and number of fighter aircraft required to meet U.S. peacekeeping needs for a year. The results are shown in Figure 2. The number and type of peacekeeping operations is the independent variable. Fighter wings required to support the operations is the dependent variable. The figure shows that if the USAF has to support two large peacekeeping operations, every element of its current 20 wing force (approximately 2100 fighters) will have to deploy during the year. Note that today the USAF is supporting one large and a number of smaller peacekeeping operations at various locations around the world. Tomorrow, who knows how many there will be.

2.1 Cost

With the changes that have taken place in the world over the last ten years, it should be no surprise that budget available for any type of defense procurement, much less fighter aircraft, is in extremely short supply. While fighter procurement has been cyclical in real terms for much of the last 25 years, budgets have been historically high. This 25-year period also saw the introduction of

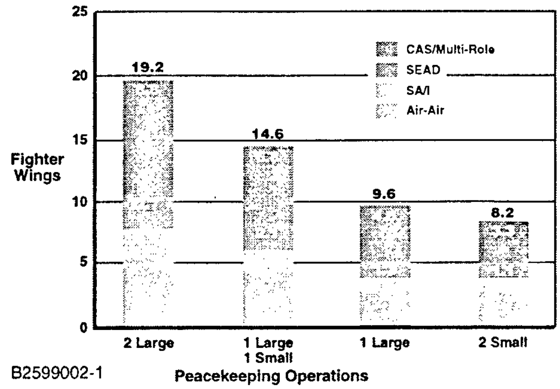


Figure 2. LMTAS Assessment - USAF Requirements

a number of impressive new fighters that substantially increased fighter force capability even though absolute numbers dropped (Figure 3).

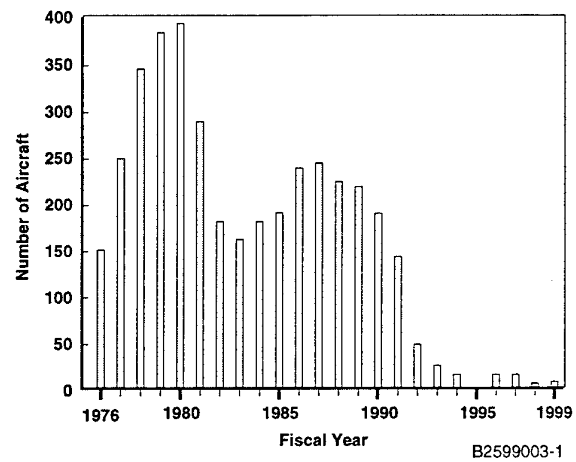
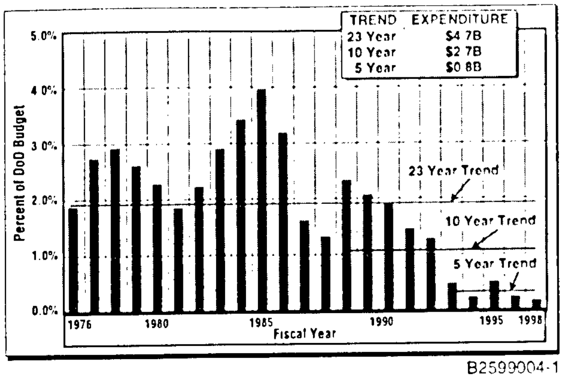


Figure 3. USAF Fighter Procurement

Then a few years ago, as all of us are well aware, the international situation changed and nothing has been the same since Fighter procurement dropped precipitously to include a year when it was zero. Simultaneously, USAF fighter force structure inventories were pared to nearly 50% of previous levels. Now planned procurements will barely keep up with attrition until new aircraft types start to enter the force in the next century. In the meantime, fighters are aging, budget pressures remain critical and all are concerned about the future.

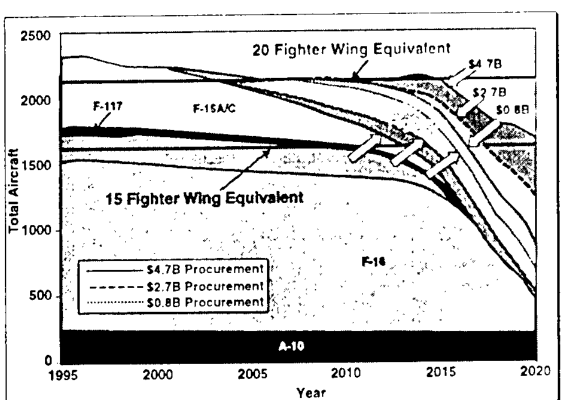
Figure 4 presents another historical perspective intended to bracket reasonable future procurement trends. Here USAF strategic/fighter aircraft procurement is combined (to reflect the blurring of the differences between tactical and strategic aircraft roles and capabilities). It shows that as a percentage of the Department of Defense (DoD) total budget, fighter/strategic procurement averaged about 2% over the past 23 years. Over the last ten years, it was about 1% and for the last five years, the average has been 0.3%.



B2599004-1

Figure 4. USAF Tactical Aircraft Percentages

Therefore, a reasonable projection for future procurements should be, at most, in this range. Figures 5 shows an internal Lockheed Martin projection of what effect these percentages would have on USAF fighter force structure through 2020 based on an assumed total DoD budget of $250B in constant dollars. Note that at the $4.7B procurement level, the planned procurement of new fighters allows the force to be maintained at current levels until about 2015. By 2020 the force structure would approach a 15 wing level of capability. At a $2.7B level, USAF starts to fall below the 20 fighter wing requirement by 2010 and below 15 wings shortly thereafter. Under a $0.8B procurement level, the force structure starts a precipitous drop in 2010 and is halved before 2020.



B2599005-1

Figure 5. LMTAS Assessment - Constrained Budget Impact

2.2 Potential Shortfall

As a result of the force structure projections discussed above, there has been healthy debate within defense circles about how deal with fighter force structure issues. One option proposed is to keep fighters in the force longer. Opponents of this option (Ref 2) argue that the average age of a USAF fighter would double to nearly 20 years by 2005. At this average age, a fighter would not be retired until it has been in service for nearly 40 years. Others believe that development of a capable new cost constrained Joint Strike Fighter (JSF) will allow USAF to maintain capability for the foreseeable future. However, there is a short term, but politically expedient, option which may be employed regardless of the outcome of the internal debate - declare that no opponent can match current U.S. capability and let fighter force structures continue to drop. Although this option has the most significant long term implications, in the short term it is politically easy to implement given the subjective nature of threat projection in today's environment. And if this option is selected as a political expedient, it will take a political crisis to reverse it. In this author's option, this crisis will occur when we find ourselves in a situation where our forces are stretched so thin that we can no longer meet minimum commitments. At that point the politicians will demand quick remedial action and we will have to be ready to respond. Based on Figure 5, this crisis could occur as early as 2005 and almost certainly will occur by 2015.

2.3 UCAV Option

As will be discussed later, the UCAV system concept has inherent features that *could* make it a low- cost option to help meet the projected force structure shortfall requirements. However, when the shortfall occurs, there will be no time to evaluate such options unless actions are initiated now. UCAV and other promising system concepts are unproven and will remain so until programs are put into place to establish feasibility, reduce technical risk and demonstrate overall system capability. Given the possibility of a decision required by 2005, we must move out quickly to explore these options , establish their technical and operational feasibility, and pursue risk reduction. Otherwise, they will not be viable future options.

3. UAV STUDIES

In recent years a number of studies have examined the need and required capabilities for UAVs of all types including UCAV (Refs 3-11). Many of these studies have been published and widely distributed. Others have had much more limited distribution. Despite the variety of the perspectives reflected in the studies, a generally consistent view of unmanned vehicles and systems emerges (Figure 6).

	URAV	UCAV
• Mission	Recce (Primary)	Strike (Primary)
• Speed (Subsonic)	Low-Moderate	Moderate-High
• Maneuverability	Low	Med-Very High
• Altitude	Low/Medium/High	Low-Med/Med-High
• Observables	Moderate-Very Low	Low-Very Low
• Payload	500 - 2000 lb	500 - 4000 lb
• Sensors	Multi-Spectral	Min-Maximum
• Bandwidth	High	Low-Medium
• Endurance	Days - Weeks	Hours - Days

B2599007-1

Figure 6. Prevailing Theme - Two System Types

3.1 UAV Types

The studies generally group UAVs into two broad vehicle categories, Uninhabited Reconnaissance Air Vehicles (URAVs) and UCAVs. Although they have similarities and some concepts could perform missions of both types, they generally have significant differences. URAVs are generally considered to be high-altitude, limited-maneuverability machines while UCAVs are seen as capable of operating over a wider range of altitudes, speeds and attack profiles, much like a contemporary tactical fighter.

3.2 UCAV System

All UCAV studies describe the concept as an overall system not a vehicle (Figure 7). The three major system elements include vehicles, control stations, and the data networks required to tie the system together and provide connectivity with the rest of the tactical environment. The role of the human operator is key to the overall system concept.

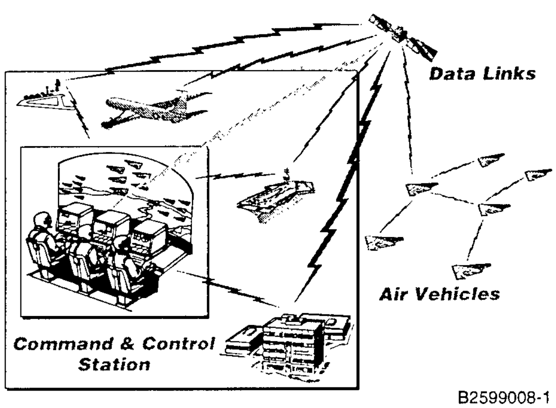


Figure 7. Overall UCAV System

The studies present a generally consistent view of the human operator as a mission level manager, not a remote pilot. High work load, time delays and lack of on-the-scene situation awareness all argue against involvement at the remote pilot level. Nonetheless, the role of the human as a decision maker is critical to the concept. In fact, the term "inhabited" was coined to convey the concept of man-in-the-loop, just not in the cockpit. To maximize decision information availability, the operator is located at an appropriate node where tactical information comes together, be it on the ground, in the air or at sea. To minimize the potential for information overload, the operator has access to software agents that handle routine vehicle and operational functions and present tactical options ranging from new mission plans to suggested tactics.

As will be discussed later, the relatively wide range of views about projected operational roles and missions resulted in an equally wide range of vehicle concepts. For example, some see the UCAV as a relatively benign vehicle operating at medium-to-high altitude carrying precision guided standoff weapons while others see it as a very highly maneuverable close-in fighting machine.

Although all studies acknowledge the importance of robust and reliable datalinks as enablers for the UCAV system concept, none were definitive about how to achieve this objective. There was agreement that controlling the vehicle at a mission level would reduce requirements for high data rate control inputs. One way to achieve this would be to have a complete mission defined on board the vehicle with operator inputs changing the existing mission plan. The vehicles, therefore, could operate on their own should data link connectivity be lost or jammed. Or they could be tightly controlled during selected mission segments, limited only by data link and band width availability. The result was a concept of control that provides inherently variable levels of autonomy. In fact, the concept of variable levels of autonomy is considered an enabler for the UCAV concept.

3.3 Benefits

The studies generally identify air-to-ground as the primary UCAV mission and cite requirements for long endurance and quick response as primary design drivers. Benefits associated with not having a human being on board are emphasized. Examples include the potential for very high maneuverability, around-the-clock operations, smaller size and, of course, no crew risk (Figure 8). Other benefits are associated with cost and include not having man-rated systems, the use of simulation to maintain operator proficiency and the ability to put the operator in the middle of the theater level tactical information network. There are, however, a number of disadvantages associated with this concept that need to be addressed. Some problems, such as the lack of on-the-scene situation awareness, the dependency on data links and the challenges of integration with manned airspace and operations are obvious. Less apparent are issues associated with integrating unmanned vehicles into an existing manned vehicle infrastructure with little, if any, experience with unmanned vehicle operations. Examples include alternate recovery fields operations, aerial refueling and recovery with live ordnance. Many of these issues can be resolved by development of appropriate procedures. Others, however, will require new technology development, the most challenging of which are related to command and control of multiple vehicles combined with constraints on connectivity and bandwidth availability.

Advantages	
• Long Endurance – Beyond Human Limits • High Maneuverability – Beyond Human Limits • High Sortie Rates – No Flight Crew Limits • Low Signature – Inherent • No Crew Risk – Hardware Only	• Small Size – Fewer Constraints • Quick Reaction – Always Alert • Low Cost – Acquisition – Training – Operations • Information Intensive • Inherent Connectivity

Concerns	
• EW Susceptibility • Reliability • Risk • Airspace Confliction	• Positive Target ID • Collateral Damage • Bandwidth • Operator Situation Awareness

B2599010-1

Figure 8. Prevailing Theme - UCAV Attributes

3.4 Missions

Despite the consistency of views about required overall performance levels and the advantages and disadvantages of the UCAV concept, generally the studies showed little consistency on the subject of projected mission application and Concepts of Operation (CONOPS). Figure 9 summarizes the range of views grouped subjectively in order of the apparent advocacy. The disparity of views is probably not surprising given the immaturity of the UCAV concept. It does, however, show that more work needs to be done to define how the concept could or should fit in to the overall theater air combat arena. In fact, CONOPS development is one of the most critical need areas associated with development of the overall system concept.

- All Studies
  - Suppression of Enemy Air Defense
- Most Studies
  - Covert Reconnaissance/Strike
  - Fixed Target Attack
  - Mobile Target Attack
- Many Studies
  - Counter Weapons of Mass Destruction
  - Theater Ballistic Missile Defense
  - Cruise Missile Defense
  - Support Jammer
- Some Studies
  - Bomb Damage Assessment
  - Offensive Counter Air (Air-Ground)
  - Defensive Counter Air
  - Offensive Counter Air (Air-Air)
  - Rescue

B2599011-1

Figure 9. Prevailing Theme - UCAV Applications

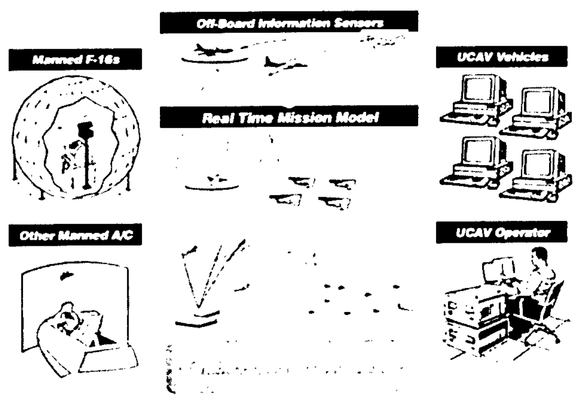
4. LOCKHEED MARTIN APPROACH

Because of the interrelationship between the overall system concept, how it might be employed and how technical issues are resolved and demonstrated, Lockheed Martin's approach to UCAV system design addresses a full spectrum of key technical, operational and programmatic issues. Independent research into potential concepts of operation has been included.

4.1 System Simulation

Early in our UCAV R&D program, we recognized the importance of simulation to develop an understanding of overall system issues. Two simulation types have been pursued, non-real time (NRT) system evaluations and real time, man-in-the-loop (MITL) mission simulation. NRT simulation has been used primarily to investigate overall system issues to include architectures and requirements and to conduct top-level trade studies of candidate solutions. MITL simulation is used to more fully evaluate selected options and to gain an understanding of operator roles and issues. MITL simulation has been particularly valuable for evaluating candidate CONOPS.

A range of NRT simulation approaches have been used, from simple physics-based system models to relatively complex system descriptions using commercial off-the-shelf (COTS) simulation packages. Our MITL simulation, however, has been based on assets and capabilities developed in support of our manned fighter product line (Figure 10). In essence we have taken a high-fidelity manned F-16 simulation complete with visual scene and physically separated the cockpit from its vehicle. The interface between the two represents a simulated data link. The cockpit displays were then modified to represent what might be a more appropriate format for an off board operator. An "outer loop" controller was created to replace stick and throttle type inputs with top level vehicle commands. For example, selecting a single "Takeoff" icon executed all of the functions and procedures normally performed by the pilot from advancing the throttle and maintaining runway alignment to retracting gear and establishing a prescribed climb profile. An existing autopilot simulation commanded the aircraft to follow a pre-loaded mission plan in a simulated Data Transfer Cartridge (DTC). We also integrated a number of highly automated advanced systems such as the Advanced Fighter Technology Integration (AFTI) F-16 digital terrain following, in-flight route replanning and automated weapons delivery systems. Finally the displays from multiple vehicles were combined in a single display to give the operator a multi-vehicle control capability. The UCAV is flown in an simulated digital mission environment which includes threats, friendly aircraft aircraft, offboard systems and support assets. To date we have used exercise-based scenarios such as a previous "flag" exercise for the mission environment.



B2599012-1

Figure 10. UCAV System Level Simulation

A number of conclusions have been reached from our UCAV system simulations. We now have a better understanding of the level of control required to remotely operate a fighter like vehicle in a rapidly changing tactical environment (Figure 11). For example, we have found that way point navigation levels of control such as those used with URAVs is inadequate in the tactical strike environment. We also have a much better appreciation for operator workload issues even with the high levels of task automation. Additional lessons learned include the effects of time delay, situation awareness, sensor and display requirements.

Since starting our initial UCAV simulation over two years ago, we have made a number of system upgrades. For example, we have integrated COTS-based variable performance vehicle and sensor

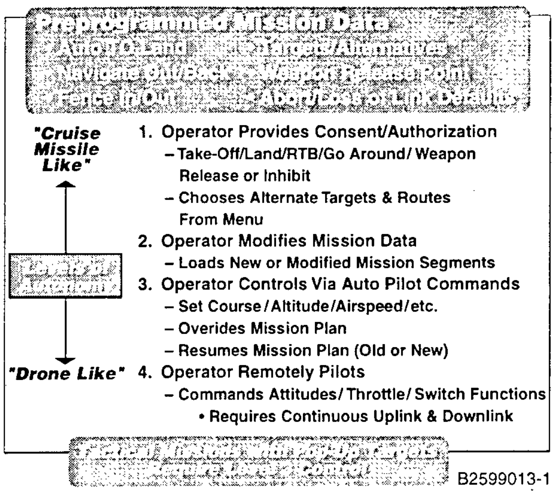


Figure 11. Variable Autonomy Control Evaluation

simulations and can evaluate a wide range of design variables such as ultra-high maneuverability, speed effects, sensor range and performance, bandwidth constraints, etc. Our ability to evaluate these and other perceived and/or preconceived requirements in the objective environment of simulation has significantly increased our understanding of UCAV issues.

4.2 New Vehicles & Systems

We are evaluating a wide range of UCAV vehicle concepts from simple modifications to existing aircraft to all new concepts, unconstrained by traditional manned aircraft design limitations. The majority of our vehicle design effort has focused on all new concepts such as the one shown in Figure 12. It is one of our larger vehicles, designed to carry inventory weapons. It is, however, smaller than a manned fighter of the same capability. This is because the man and man related equipment in a typical fighter generally constitutes 10 % of its gross weight and, when removed, results in a smaller and lighter vehicle. Or by converting the weight and volume to additional fuel, it would have greater range and/or payload. For example, a manned fighter with a fuel fraction of 25% could in an unmanned form, have a 35% fuel fraction. The corresponding increase in cruise range or radius could be as much as 50%.

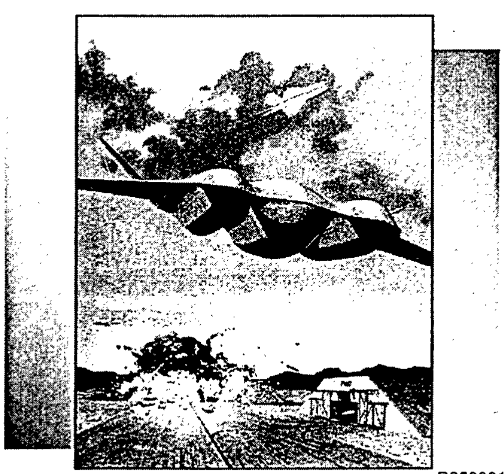


Figure 12. LMTAS Multi-Mission UCAV Concept

Other concepts under evaluation at LMTAS include totally new overall systems. Figure 13 shows an example; a revolutionary short takeoff, vertical landing (STOVL) UCAV operating off of a small surface combatant capable of launching cruise missiles and UCAVs. This overall weapon system concept calls for a capability to support a complete, albeit limited, air campaign without any support from the traditional carrier fleet. It also features a highly-automated, below deck, maintenance and weapon loading system that allows the ship to operate with a very small crew by contemporary standards.

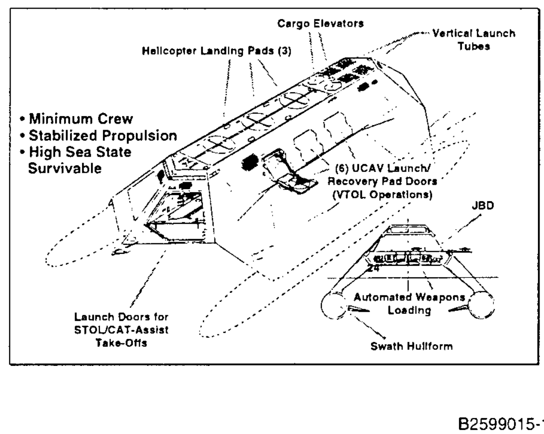


Figure 13. LMTAS STOVL UCAV System Concept

4.3 Demonstration

There are a number of issues associated with the UCAV concept that must be demonstrated to verify that projected cost and operational effectiveness advantages are anything more than optimistic projections. LMTAS is supporting a number of such demonstration planning activities. For example, we are one of the prime contractors involved in the AFRL-sponsored FATE program. We have also been exploring a number of related demonstration opportunities. Most are based on the F-16, already one of the most highly automated fighters in the USAF inventory (demonstrated or operationally deployed capabilities include a digital terrain system based automatic ground collision avoidance, a tactical datalink that allows target coordinates to be transmitted directly to the cockpit and highly automated in flight weapons delivery modes). A number of candidate demonstrator platforms have been proposed for consideration, including the AFTI F-16, the Variable In-flight Stability Technology Augmentation (VISTA) F-16 and UCAV specific demonstrator platforms based on early model F-16s (Figure 14). We also have suggested a number of related activities to include storage, supportability and aerial refueling evaluations/demonstrations.

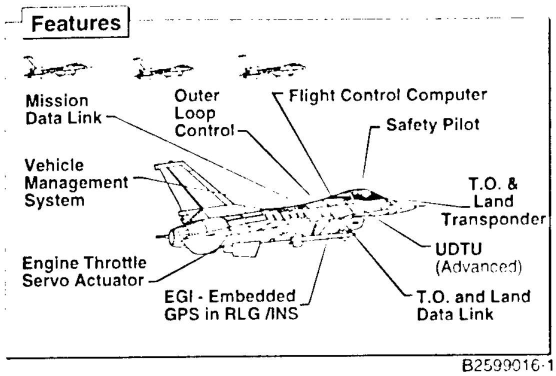


Figure 14. Proposed F-16 Based UCAV Demonstrator

4.4 Derivative Concepts

Although the focus of our efforts has been on all-new vehicle and system concepts, we have also addressed near term derivative concepts. Figure 15 is an example. It shows how an early UCAV capability might be developed by putting a thick, 60 foot (18.2 m) wing on an early model F-16. This vehicle would be capable of carrying fighter size external payloads but have unrefueled range and/or endurance that would far exceed any contemporary fighter. As a consequence we have dubbed it the Long Endurance Derivative (LED).

It would have the capability to perform long endurance, continuous combat air patrol (CAP) type missions which manned fighters currently fly but do so relatively inefficiently because of their comparatively short range and/or time-on-station. It is well known, for example, that it can take a squadron of manned fighters to maintain a CAP for a 24-hour period. As shown in Figure 16, a LED-type squadron could maintain 12 CAPs under the same conditions. In comparison to contemporary UAVs, the LED would be able to perform missions which are not possible today because of payload and/or power and cooling constraints.

5. FUTURE FORCE MIX

One of the key issues facing those working UCAV concepts and technology has been the question of what, if anything, the system concept might be called upon to do in the future. Our first inclination was to survey the literature for guidance. Nothing substantive, however, was found. Therefore, we elected to try to answer the question ourselves. We had former operators on our IPT and we took on the subject using their background and experience and lessons learned from our UCAV system simulator.

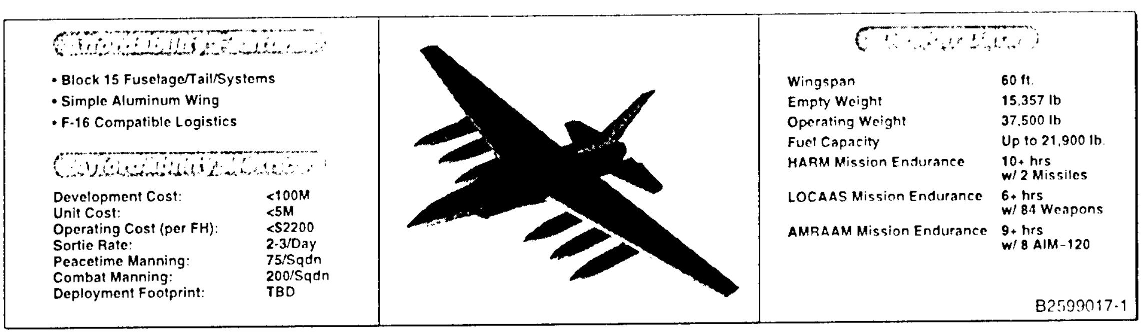


Figure 15. F-16 Based Long Endurance Derivative

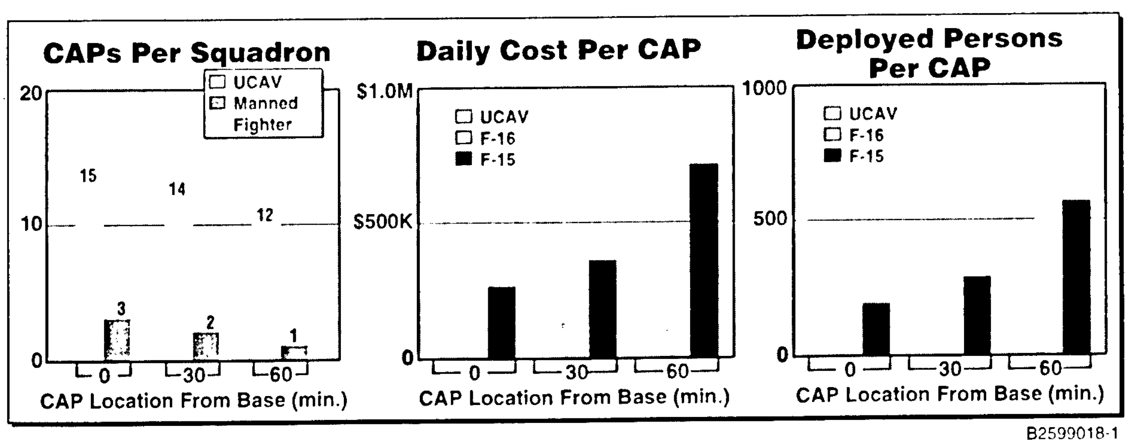


Figure 16. Long Endurance CAP Capabilities

5.1 Manned and Unmanned Mix

Early in our investigations we concluded that the UCAV would not be a stand-alone weapon system. The tactical air environment is too complex and there is too much interdependency among the elements of the tactical force. The question, therefore, was what role might the UCAV play and how might it integrate operationally, logistically and technically with the rest of the tactical force.

Figure 17 shows a typical tactical air battle environment in which a number of weapon and support systems interoperate. Included are air-to-air fighters that provide overall air superiority over the battlefield, multirole fighters that attack a range of targets both fixed and mobile, standoff missiles that attack heavily defended ground targets, close air support (CAS) helicopters and aircraft that operate in direct support of ground troops, reconnaissance systems to provide the battlefield commanders with information on the developing tactical situation and various tactical support assets such as JSTARS and AWACS that help tie together and coordinate the overall air and ground battle. Included but not shown are specialized, highly-survivable deep strike aircraft that carry the air battle deep into enemy territory and attack critical command and control and other specialized targets. Also shown is a UCAV. Its role, however, is not defined although some candidate roles are suggested as shown. The question is: are these the right roles and missions for the various tactical system elements if and when the UCAV becomes a viable tactical alternative?

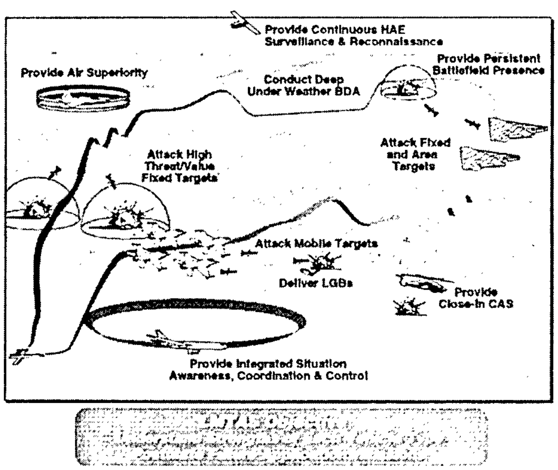


Figure 17. Projected Future Force Mix

5.2 Roles and Missions

Based on the studies previously referenced, results of MITL mission evaluations and qualitative evaluation of potential mission requirements (Figure 18), we offer for consideration our preliminary assessment of potential roles and missions for three existing tactical systems (manned fighters, cruise and ballistic missiles and UAVs) in the near term (2005-2010) and how they might evolve in the longer term (after 2015) as a result of UCAV introduction.

In the near term UCAV should have only minor impact on the manned fighter and cruise and ballistic missile forces. One reason is our projection of a U.S. defense shortfall that will materialize during the period 2005-2015. All of the existing systems in the inventory, therefore, will be required to compensate. Another reason is our assessment that UCAV will be introduced to perform jobs that are not already being done. Therefore, assuming that UCAV has gone through a rigorous technology and operational feasibility and effectiveness evaluation that allows it make a successful entry into the force, only in the longer term would we expect to see an impact (as shown in Figure 19). From the fighter perspective, we project that the most significant far term impact will be to divert fighters away from one traditional mission, attack of fixed ground targets. But this will only occur if UCAVs have demonstrated their ability to execute these types of missions and to be cost and operationally effective. We see a similar impact on cruise and ballistic missiles, however, we project that upon entry into the force, UCAV would pick up low-threat, fixed target attack missions where missiles are used only to eliminate any risk of crew loss or capture. In the longer term, we project that UCAV would pick up all but the highest threat fixed target missions, those

- Information Dominance
  - Gather/Assess/Decide in Near Real Time
  - Deny Adversaries Same Capability
- Absolute Air Superiority
  - Maintain Freedom From/To Attack
  - Increasing Emphasis on Ballistic and Cruise Missiles
- Persistent Presence
  - Continuous Observation/Assessment
  - Round-the-Clock Planning/Attack
  - Operate Any Time/Any Weather
- Near Instantaneous Strike
  - Anticipate/Dominate Changing Tactical Situation
  - Intimidate/Destroy Time Critical Targets
- Minimum Collateral Damage
  - Selective Force on Specific Targets
  - Discrete and Dominant Effect
- Minimum Cost and Risk
  - Lowest Cost Per Kill (or Other Mission Objective)
- Maximum Flexibility
  - Deployment/Employment

B2599020-1

Figure 18. Overall Goals & Requirements

Fighters	Near Term	Longer Term
Missions	Air Superiority Multi-Role Mobile Targets Fixed Targets Low-High Threat	Air Superiority Multi-Role Mobile Targets Low-Moderate Threat
Envelope	Subsonic/Supersonic Medium-High Altitude	Subsonic/Supersonic Medium-High Altitude
Payload	Inventory Sensors Inventory Weapons	Inventory Sensors Inventory Weapons
Survivability Features	Stealth Speed Standoff Countermeasures	Stealth Speed Standoff Countermeasures

Cruise/Ballistic Missiles	Near Term	Longer Term
Missions	High Value Fixed Targets Moderate - High Threat	High Value Fixed Targets High Threat
Envelope	Low/High Altitude Subsonic/Hypersonic	Low/High Altitude Subsonic/Hypersonic
Payload	Unitary/Cluster Munitions	Self Guided Weapons
Survivability Features	Altitude/Signature Speed	Altitude/Signature Speed

B2599021-1

Figure 19. Force Mix Evolution - Fighters and Missiles

that from a survivability vs. cost effectiveness perspective are best left to expendable systems for execution.

In the near term UCAV should have little impact on primary URAV roles and missions (Figure 20). High-altitude, long-endurance reconnaissance and surveillance will continue to be a critical theater-wide need and current and projected URAVs are ideally suited for this mission. The only exception might be under the weather bomb damage assessment (BDA), a mission that requires an aggressive low-to-medium altitude flight profile to survive. There are also secondary missions for which UCAV may be better suited. For example, there have been reports that URAVs are being evaluated as long-endurance weapons platforms. Although these are only studies and no decision has been made, those of us in the tactical aircraft community know that it takes a lot more than an external hardpoint and desire to turn an air vehicle into a weapons platform. Ejection loads and dynamics, flight and ejection clearances, stores management system design, reliability, harness routing, and a multitude of other considerations make it extremely difficult to adapt a vehicle for weapons carriage if it was not originally designed for this role. In fact, the number of successes can probably be counted on one hand. We suspect, therefore, that these latest attempts will meet a similar fate and that the requirement will be met by near term UCAVs. Another secondary URAV mission for which a near term UCAV may be well suited is as a high power communication relay and/or support jammer. Both of these missions involve equipment that require significant amounts of on-board power and cooling in addition to their weight, volume and required aperture areas. We suspect the current generation URAVs will have a difficult time meeting these requirements and that they too will be met in the near term by first generation UCAVs such as our LED concept (Figure 15).

Although not specified in Figure 20, almost all of the near term UCAV roles are expected to be air-to-ground. The only possible exception is a defensive air-to-air role such as a high value asset

URAVS	Near Term	Longer Term
Missions	Recce/Surveillance Comm. Relay Low/Med/High Threat	Recce/Surveillance Comm. Relay Low/Med/High Threat
Envelope	Subsonic Low/Med/High Altitude	Subsonic Med/High Altitude
Payload	Low Power Sensors/ Comm. Relay	Sensors/Comm. Relay
Survivability Features	Stealth/Countermeasures or Standoff	Stealth/Countermeasures or Standoff

UCAVS	Near Term	Longer Term
Missions	CAP Type Fixed Targets Time Critical Targets Battlefield Support Under-the-Weather BDA Low-Moderate Threat	Multi-Role Fixed Targets Time Critical Targets Mobile Targets Under-the-Weather BDA Low-High Threat
Envelope	Subsonic Medium-High Altitude	Subsonic/Transonic Low-High Altitude
Payload	Inventory Weapons High Power/Cooling Equip.	Low Cost Sensors Low Cost Weapons
Survivability Features	Stealth Countermeasures	Stealth Countermeasures Maneuver

B2599022-1

Figure 20. Force Mix Evolution - UAVs & UCAVs

barrier CAP as currently being flown by manned fighters in defense of AWACS, JSTARS and other potentially vulnerable support platforms. A long endurance UCAV carrying BVR missiles should be capable of performing this mission more cost effectively than a manned fighter and allow the latter to be deployed elsewhere in the battlefield where on the scene human presence is a more critical requirement.

In the longer term, we believe that new URAVs will be designed from the beginning for large payloads and will have sufficient power, cooling, weight, and volume margins to pick up some missions from near term UCAVs. We doubt, however, that they will be survivable enough at low altitudes and/or below the weather and that this regime will be covered by UCAVs. Otherwise, the URAVs should continue to be the premier intelligence, surveillance and reconnaissance eyes and ears of the battlefield and national commanders. And in the longer term, we expect the UCAV to perform a wider range of air-to-ground missions to include having a capability for finding, identifying and attacking mobile targets. Traditional air-to-air missions, however, will probably continue to be manned fighter territory.

6. PROGRAM APPROACH

Three years of intensive R&D on the UCAV concept has convinced us that an all-new UCAV system able to exploit the inherent advantages and disadvantages of manned and unmanned systems will be required to achieve the full potential of the concept. However, development of this system much less its enabling technologies cannot take place in the absence of a good set of design and operational requirements. A UCAV development program, therefore, should include:

1. Operational and technical evaluations using simulation and flight experimentation to explore a general UCAV concept of operations, tactics and configuration-independent design and technology requirements. Included would be: how the UCAV would integrate with manned aircraft (military and civil), connectivity issues, command and control, and how vehicles would be stored, deployed, supported and recovered. There are a number of candidate vehicles that could be used for this effort, ranging from existing UAVs to manned fighter-based demonstrators. The output to this UCAV thrust would be a generic UCAV concept, lessons learned from simulation and flight experiments and a validated set of general requirements for which an all-new UCAV system could be designed.

2. All-new UCAV concept development and demonstration. This would focus on configuration-specific capabilities and technologies. For example, an ultra-high maneuverability UCAV would require development of technologies and capabilities unique to that concept. While its capabilities could be evaluated in simulation, no existing vehicle could emulate its unique flight characteristics much less evaluate its enabling technologies. The output of this UCAV thrust would be a preferred UCAV concept, its enabling technologies, lessons learned from simulation and flight experiments and a specific set of requirements for an operational UCAV system.

We believe it is essential that both elements should be included in the near term development program (Figure 21). The initial flight evaluations, however, should be completed before first flight of the all-new concept. This would provide the new vehicle with a validated overall system in which to operate and let its flight demonstration focus on a reduced set of configuration-specific issues.

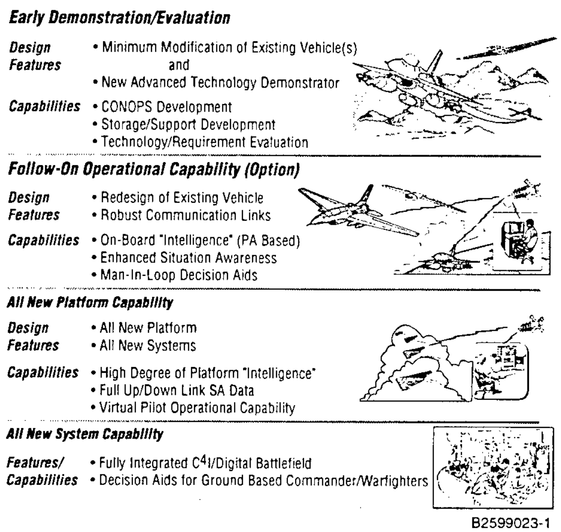


Figure 21. Phased Program Approach

7. CONCLUDING REMARKS

With the successful conclusion of the overall UCAV system and configuration-specific technology demonstration, we believe defense planners would have a sound basis for deciding whether UCAV is a viable candidate for redressing our projected future force structure shortfall. If a near term shortfall materializes, it might be addressed by redesigned or productionized versions of the demonstration vehicles. If the shortfall is less time critical, one could pass on the intermediate option and focus all resources on the all-new system concept. Either option could be pursued knowing that the key issues are well understood and that a real solution that meets requirements will result.

8. REFERENCES.

1. Chaput, A.J., et al., "Unmanned Tactical Aircraft - A Lockheed Martin Perspective", AGARD CP-591,October 1995
2. Spinney, F.C., "Defense Budget Time Bomb", Public Hearings, February 1997
3. Francis, M., "Unmanned Tactical Aircraft", Defense Advanced Research Projects Agency, July 1995
4. Shepard, C. et al., "Quick Look Study", Air Force Material Command (AFMC), October 1995
5. McCall, E., et al., "New World Vistas", USAF Scientific Advisory Board (SAB), December 1995
6. Worch, P., et al., "UAV Technologies and Combat Operations", USAF SAB Summer Study, September 1996
7. Rieman, J., et al., "ACC/AFMC Air-to Surface Development Plan", AFMC, September 1996
8. Palfalvy, G., et al., "Highly Maneuverable Lethal Vehicle", Naval Air Weapons Center, October 1996
9. Fogleman, R., "Global Engagement", Air Force 50th Anniversary Exhibit Opening, Smithsonian Institution, November 1996
10. Atherton, C., et al., "LMTAS Future Tactical Aircraft Study", Management Briefing, December, 1996
11. Moul, T., et al., "Revolutionary Capabilities For UCAV, NASA Langley Research Center, February 1997

9. ACKNOWLEDGEMENTS

The support of the following individuals is gratefully acknowledged:

My colleagues at LMTAS who provided invaluable insight and support: Dr. John V. Kitowski, Systems Engineering; Mr. Brian Jackson, Operations Research; Mr. Dave Cooper, Systems Development Center; Mr. Mark Witte, Configuration Development; Mr. Robert Ruszkowski, Configuration Development; Mr. Steve Weigel, Weapon System Integration; Mr. Ed Brungardt, Information Warfare; Mr. Allan Hill, Support System Integration; Ms. Jean Fox, Systems Development Center; Ms. Kathi Sessums and Ms. Rhonda Benson, Engineering Graphics; Ms. Sherri Ray, Proposal Development Center.

My daughter, Ms. Jenny Chaput, who applied her considerable and professional editorial skills to this manuscript.

CONOPS of HALE UTA in an InfraRed Early Warning mission for Theater Missiles Defense

Hervé Gilibert
Defense Systems Preliminary Design Department
Extended Air Defense Systems design
Aérospatiale Espace & Défense
BP n° 3002 - 78133 Les Mureaux Cedex
France

Régis Thevenot
Defense Systems Preliminary Design Department
High Altitude Long Endurance UTA Systems design
Aérospatiale Espace & Défense
BP n° 3002 - 78133 Les Mureaux Cedex
France

LIST OF ACRONYMS

ATBM	Anti Tactical Ballistic Missiles
C2	Command and Control
C3I	Command, Control, Communications, Intelligence
COMINT	COMmunications INTelligence
CONOPS	CONcept of OPerationS
DSP	Defense Support Program
ELINT	ELectronic activity INTelligence
HALE	High Altitude Long Endurance
IR	InfraRed
IRST	InfraRed Search and Track
LEO	Low Earth Orbit
LWIR	Long Wave InfraRed
MTI	Moving Target Indicator
MWIR	Mid Wave InfraRed
NATO	North Atlantic Treaty Organization
OOA	Out Of Area
SBIRS	Space-Based InfraRed System
TBM	Tactical / Theater Ballistic Missile
UTA	Unmanned Tactical Aircraft
WMD	Weapons of Mass Destruction

1. SUMMARY

This paper presents the concept of High Altitude Long Endurance UTA equipped with InfraRed sensors for Tactical Ballistic Missiles (TBM) detection and tracking.

After a short presentation of the general context of operations in an Anti Tactical Ballistic Missile (ATBM) defense system, the IR HALE concept is depicted in its technical aspects as well as in its operational aspects :

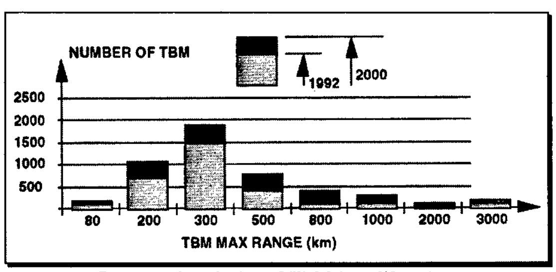
- analysis of potential "observable features" (signatures) of missiles, and crossing with general ATBM defense needs leading to introduce the IR HALE concept,
- analysis of its potential performance levels in two major observation functions (missiles detection and tracking), derivation of a preliminary design,
- exploration of major operational features (survivability, ...),
- synthesis of these elements :
  - analysis of defense capabilities in typical TBM "Out of Area" scenarii,
  - potential roles inside global ATBM defense systems, for Early Warning and Weapon Systems commitment,
- description of the command and control segment of such a system and its integration into air operations,
- brief overview of the other missions that can be envisioned for such a UTA.

Concluding remarks highlight the position of the IR HALE UTA concept among other Early Warning / Cueing systems, both in terms of technical performance and military concept of employment.

2. INTRODUCTION

As was demonstrated during the recent Gulf war, attacks of NATO nations troops by Theater Ballistic Missiles are now a highly probable risk in Out Of Area (OOA) operations.

Current proliferation monitoring indicates trends that will lead non NATO nations to be able to reach the southern and central part of Europe by using medium range TBM fired from their own territory : current indigenous developments in Middle East Area and South Mediterranean countries (sometimes supported by North Korean help) are preparing new TBM with ranges of 1000 to 1500 km, thus capable of crossing the Mediterranean sea.

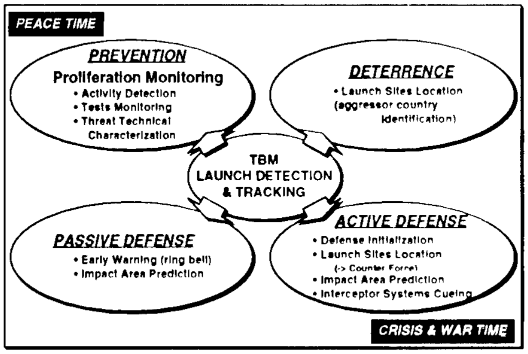


Status and evolution of TBMs' proliferation.

Several studies have been carried out in France in order to analyze possible postures of defense and needed defense systems against such a threat.

Paper presented at the AGARD MSP Symposium on "System Design Considerations for Unmanned Tactical Aircraft (UTA)", held in Athens, Greece, 7-9 October 1997, and published in CP-594.

At the end of these analyses, the ability to ensure ballistic activity monitoring in peace time, battlefield surveillance, TBM detection and tracking in crisis / war times appears to be the cornerstone of all defense policies, whether prevention, deterrence, passive defense or active defense.



TBM launches detection capability as the cornerstone of all defense postures.

Through its participation in these studies, AEROSPATIALE has highlighted a very promising new concept for performing this part of defense functions (usually called Early Warning and cueing of weapon systems) : an InfraRed sensors equipped High Altitude Long Endurance (HALE) Unmanned Aerial Vehicle (UTA) should have impressive operational performance, while being "easily" affordable.

The purpose of this paper is to present the overall IR HALE UTA concept, both in its technical and operational aspects.

At the intersection of these two aspects, the presentation will show how its needed technical features for achieving high level performance (especially flight altitude, ...), do converge with the operational use requirements and constraints (survivability, aircraft control, ...) for making it a particularly attractive concept.

3. ATBM Architectures

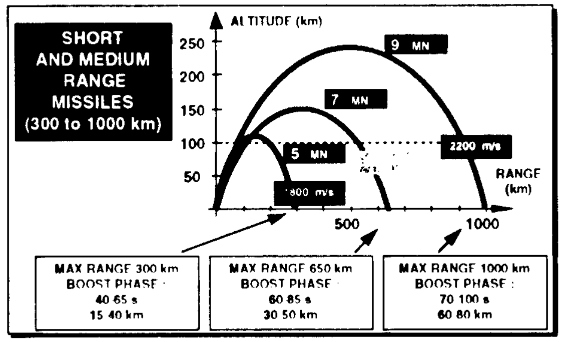
3.1 The threat

From a military point of view, Theater Ballistic Missiles have been shown to be a real threat during Gulf War. Their military efficiency was far smaller than their psychological effects, since they were equipped with conventional warheads, but the use of WMD warheads (Weapons of Mass Destruction) such as chemical ones, represents a high probability / high lethal risk in future comparable conflicts.

From a technical point of view, many countries now have the capability of deploying and using Theater Ballistic Missiles with ranges varying between 120 km and more than 2000 km.

Such missiles usually have a nominal apogee altitude which is about 25 % of the range, i.e. between 30 and 500 km of altitude.

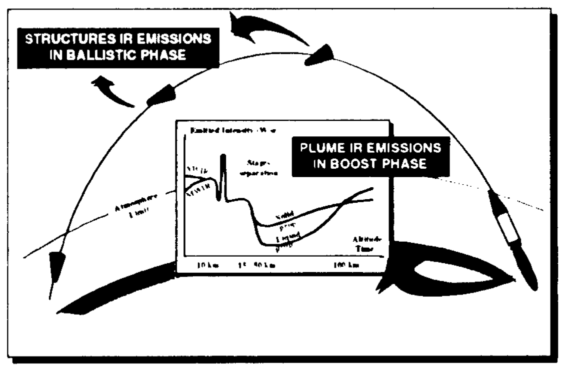
Initial boost phase may last between 20 to 120 s, and correlatively burnout may occur between 10 and 150 km altitude, depending on the missile range, the number of stages and the nature of the propellant (liquid or solid).



Short range TBM trajectory and boost phase characteristics

During this short boost phase (typically less than 15 % of the flight duration), the missile plume delivers very intense InfraRed emission, especially in Mid Wave InfraRed band (MWIR), providing a high signature that can be detected even by geosynchronous satellite systems such as US DSP (Defense Support Program) satellites that look at them over earth background.

The burnout event does not necessarily mean the disappearance of the missile InfraRed signature since some parts of it were heated during the ascent phase in the atmosphere : nose part structures, rear fins (if present), and, of course, the nozzle (if not masked by missile rear structures).



TBM plume and structures emissions in IR wavelengths.

Indeed the heating of the nose part leads to high level InfraRed signatures (mostly in M-LWIR : Mid to Long Wave InfraRed band), with high contrast when observed against a sky background. This signature remains quite constant during the ballistic phase, making it possible to track the missile throughout this phase. This drives for example the US concept SBIRS-LEO (Space-Based InfraRed Sensors - Low Earth Altitude satellite system : former Brilliant Eyes system).

As the missile flight in the ballistic phase is fully deterministic, very simple algorithms (typically based on Kalman principles) give high precision trajectory prediction, even with a rather small number of medium accuracy measurements ...

3.2 ATBM defense systems functions and architectures

Associated to the different possible defense policy in front of TBM attacks,

- passive defense, sending threatened people into shelters,
- active defense, committing interceptors against incoming missiles.

- or counterforce, sending attack weapons against TBM launch sites or aggressor's high value sites.

The required functions for ATBM defense systems are :

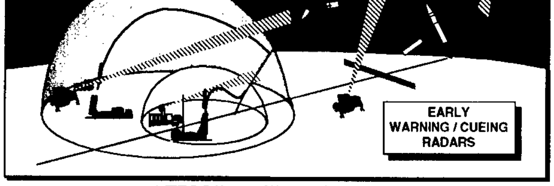
- TBM launch surveillance and [early] detection (Early Warning),
- TBM launch site location,
- Threatened sites / areas determination through ballistic trajectory prediction,
- TBM inflight destruction by interception systems.

If we consider not only the crisis / war phase of conflicts involving Tactical Ballistic Missiles, but also peace time, some other essential missions must be added for ATBM defense systems, related to Intelligence function :

- ballistic activity (flight tests ...) surveillance,
- TBM technical characterization (intelligence purpose ; defense readiness improvement, ...).

«Classical» ATBM architectures for meeting these needs are made of :

- Early Warning Satellite Systems (such as US DSP), in charge of wide area surveillance, TBM launch detection & location through IR plume signature ; their ability to predict the ballistic trajectory and estimate impact point location is generally rather limited.
- Medium-Long Range radars also capable of surveillance, and generally dedicated to the accurate tracking of TBM in order to provide precise estimate of impact point and precise cueing data for interceptors guidance. These radars are themselves often cued by the Satellite System.
- One to several families of interceptors : theater high altitude interceptors (see US Navy Theater Wide, US THAAD, ...), or low endo interceptor systems such as US Patriot / ERINT, Aster missile (Fr / It), where the interceptors are associated to smaller, dedicated "Fire Control Radars". Due to the small size of the defended area they provide, the latter are usually called "Point Defense Weapon Systems".
  These interceptors families may be deployed simultaneously on a given theater, for enhancing defense efficiency through successive layers and shoot-look-shoot policy.



ATBM "usual" architectures

3.3 Introduction of InfraRed Airborne sensor systems in ATBM architectures

When we look at needed functions in an ATBM defense system and at the "observable features" of Tactical Ballistic Missiles that are described here above, we can rapidly imagine a conceptual observation system fulfilling a large number of needed observation functions.

Indeed, since TBM plumes can be detected from geosynchronous orbit, by sensors looking for them against earth background, they should be detected by comparable sensors placed on aerial platforms, and looking for them against [less emissive and less cluttered] limb / sky background : the penalty due to transmission losses on a rather horizontal line of sight will not lead, of course, to a 36000 km detection range (which is not needed in that case !), but transmission laws indicate that today achievable high flight altitudes lead to «high» transmission coefficients.

Moreover, the observation configuration of InfraRed sensors on airborne platforms is particularly favorable for targets tracking after their burnout, as we have already mentioned. The contrast against sky background is high, while transmission rate improves with line of sight elevation.

Thus appears the concept of «Early Warning / Early Tracking / Early Cueing» InfraRed High Altitude airplane.

Starting from these assessments about general principles, our technical analyses did confirm the high performance levels that it can achieve, and led us to go further into overall design and evaluation.

4. PERFORMANCE AND DESIGN OVERVIEW

4.1 Detection and tracking performance

The two major parameters which determine the detection range of an IR airborne sensor looking for TBM plumes against limb / sky background are :

- the sensor IR observation wavelength band,
- the platform altitude.

The choice of the first parameter is driven by the spectral characteristics of plume emission (depending on propellant nature : liquid / solid), the spectral characteristics of atmosphere absorption on the line of sight, and the spectral characteristics of background emission (mean level and clutter). In that area, the trade-off analysis leads to privilege the MWIR band.

The choice of the second parameter is driven by two factors, the [lowest] integrated transmission on the line of sight, and the [lowest] risk of presence of clouds on the line of sight. Of course, the first of these two factors has to be selected in relation with the IR band selection.

IR transmission rate variations as a function of the sensor altitude show that TBM plume detection ranges do increase when platform altitude varies from 15 to 18 km, and has less significant increase when taking higher altitudes.

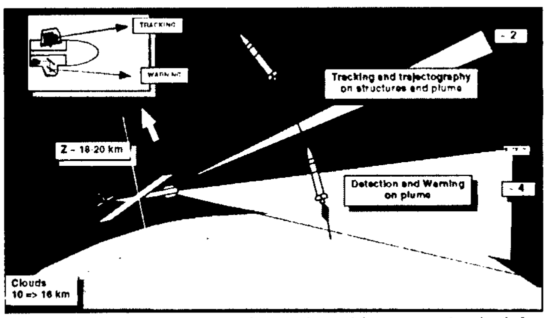
The non-interception of the line of sight by clouds means as well that the platform must fly over 15-16 km (especially in subtropical area).

So, the first essential conclusion is drawn : the IR sensor in charge of TBM plume detection has to be carried at rather high altitudes, typically 18 km and higher.

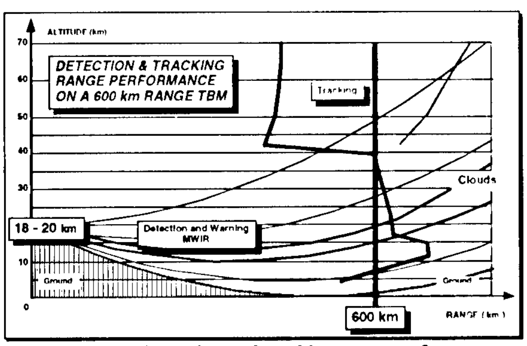
In these conditions, estimated performance is very impressive : TBM plume detection range is found between 600 and 8-900 km, depending on the TBM class (from SCUD B / Al Husayn class, having a range of around 300/600 km, to longer range missiles with ranges up to 2,000 km and more). The detection range is comparable with (sometimes higher than) the missile range ...

As far as the detection and tracking of TBM structures after booster burnout is concerned, the IR band trade-off analysis calls for slightly higher wavelengths, while tracking performance (impact point early and accurate prediction) makes it necessary to reach high observation elevations, typically 60° or more.

Tracking ranges are estimated to be quite equivalent to plume detection ranges on current proliferated missiles, so that a continuous detection and tracking process can be envisioned, on the first part of TBM flights (up to apogee area).



IR HALE UTA : TBM detection and tracking general principles



IR HALE UTA Detection and tracking range performance on a 600 km range TBM

In terms of trajectory prediction accuracy, the results obtained are impressive as well : impact point predictions with accuracy better than 5 km (diameter) are delivered before the TBM reaches its apogee, so that the remaining time for alerting populations or troops in the estimated area ranges from 3 to 6 minutes, depending on the TBM range (300 to 2000 km). This is also the time available for preparing the acquisition of the target by ATBM Point Defense Weapon Systems.

These results are obtained by simply using one passive InfraRed Search and Track sensor (IRST), i.e. without need for distance measurement (which could be provided by Laser rangefinder), and even without need for stereoscopic observation (which would require the association of two airborne systems for each surveyed area and thus multiply the number of loitering airplanes by a factor greater than two).

The gains assessed in presence of Laser rangefinder and / or stereoscopic observation are significant in terms of tracking duration, more than in terms of final accuracy.

	Single sensor observation	Stereo observation or laser telemetry
Flight duration	445 s	445 s
Apogee	163 km	163 km
Time for Apogee	250 s	250 s
Impact with 10 km error	213 s / 155 km	110 s / 80 km
Time before impact	232 s	335 s

Tracking accuracy sequence vs observation configuration

Single passive observer performance appears to be generally sufficient in that area of alert delay, so that the other two solutions do not really bring anything more. The single passive observer is then our basic assumption in the next paragraphs.

4.2 Design overview

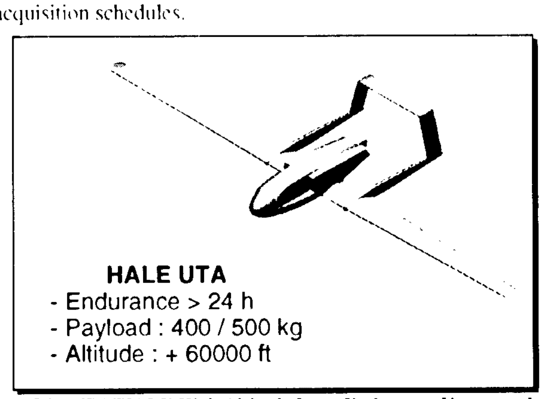
Previous elements define the primary requirements for the IR sensors and High Altitude airplane design.

Associated with a certain permanency needed in surveillance operations, the objective of overall operations cost reduction means searching for a small number of airplanes on the ground per airplane in flight, which leads to Long Endurance requirements. Cost analyses and confrontation with capabilities offered today by aeronautical technologies make it quite easy to design airplanes with 24 hours and more loitering duration.

Such flight duration and the interest of not having large pressurized volumes on such airplanes pull towards unmanned aircraft solutions.

*Thus, the concept becomes naturally an IR High Altitude Long Endurance Unmanned Tactical Aircraft **(IR HALE UTA)**.*

Preliminary design studies of 65000 ft IR HALE UTAs have been undertaken for ensuring the concept's feasibility, inventorying the technical difficulties, confirming system performance, and estimating costs and development / acquisition schedules.

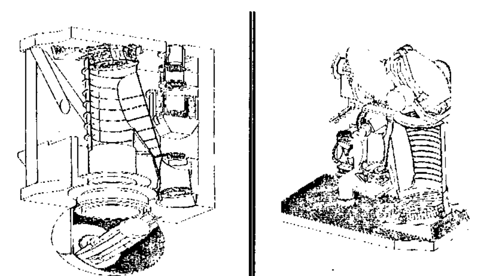


AEROSPATIALE High Altitude Long Endurance Unmanned Tactical Aircraft conceptual design.

These studies have led to 2 major design options, as far as sensor integration is concerned :

- a «double pod» design, with :
  - one pod mounted (partially included inside the airframe) under the aircraft, and in charge of 360° azimuth surveillance. This sensor is looking in horizontal directions and slightly downwards in a small elevation angular sector (a few degrees). Its role is TBM plume detection, and cueing preparation for rapid acquisition by the top mounted sensor.
  - one second pod mounted (partially included as well) on the top of the airframe. Its sensor is in charge of TBMs tracking at the end of their boost phase and during their ballistic phase. Its rather small Field Of View (a few degrees^2), is mechanically moved in a large Field Of Regard (up to 60° and more in elevation ; 360° in azimuth).

  This «double pod» design provides for large surveillance and tracking sectors, only limited by rather small airframe masks. But its major drawback is the penalty on the aircraft drag, compared with following more integrated design.



Sensor designs in "double pod" integration option

- a «nose mounted» design, with two similar instrument solutions placed in front of the aircraft.

  This design gives smaller [azimuth] Fields Of Regard because of large rear mask due to the airframe, but this can be compensated by use of adapted loitering profiles (such as «8 shaped trajectories»), when surveillance is not needed in a 360° azimuth angle. One of its major advantages is the fact that the sensor is fully integrated inside the airframe, which gives better aerodynamical performance and offers opportunities for using the platform as a multimission one (design of removable payload).

5. IR HALE UTA OPERATIONAL FEATURES

5.1 A «natural» survivability ...

Defense systems design does not often bring such converging technical and operational features as the IR HALE UTA.

As a matter of fact, its needed technical characteristics lead naturally to a high survivability level :

- its high loitering altitude (65,000 ft) makes it unattainable by most of Air Defense Weapon systems in the world.

  The primary reason for this high survivability in a large number of [low to medium Air Defense threat level] scenarios is its low detectability : the needed cruise altitude is above current radars search ceiling, and robustness against possible (certain !...) improvements of these radars can be achieved by applying simple stealth design rules.

  Moreover, the observations through a fully passive sensor do not mark the presence of the aircraft : discretion is an other virtue of the concept ...

  Let's add that even in case of detection, the high flight altitude of the platform is also a protection against the majority of interceptors in the world, being above their flight domain.

  These features let us envision a safe use of the UTA very close to or even over hostile territories, in a great number of scenarios.

- in front of highly defended territories, a stand-off distance from hostile territory must be kept. But, even in the worst cases (for instance presence of SA-12 Air Defense systems), the subtraction of the needed stand-off distance from the sensors detection and tracking range still provides for a long observation depth inside the surveyed area : typically 400 to 6-700 km.

5.2 A useful flight altitude ...

The high flight altitude, provides an additional advantage (useful only when loitering is over allied territories) : it is higher than Controlled Airspace ceiling, so that operations can be achieved in a total free way between the climb and descent phases.

Nevertheless, this does not mean the absence of any control during the cruise phase : platform / payload integrity and mission controls remain of course necessary !

6. IR HALE UTA CONCEPT OF OPERATIONS

6.1 Deployment analysis

Short term scenarios will involve TBM with ranges lower than or just exceeding the IR HALE UTA detection range : from SCUD B missile to No-DONG missile. Except in the case of the latter one, shot against targets very close to the enemy area's border, the IR HALE UTA range will be sufficient for operating close to the border, with the adapted stand-off distance if necessary.

In most envisionable Out Of Area conflict scenarios, the border or coast length is not longer than 1,000 to 1,500 km, so that surveillance of TBM launches can be performed by up to three loitering HALE UTAs.

However, in the future or today in some particular cases, proliferating countries will be capable of in depth attacks from in depth (on their own territory) launch pads. In that case, additional (typically one or two) systems will be needed for in

depth surveillance, either by flying over enemy territory or from rear allied territories.

Let's note here that the long endurance of the HALE UTA concept makes it possible to have one common base for all UTAs in such a configuration : indeed, the long loitering endurance can be partially traded-off for projection range. When surveyed countries are not too far from NATO nations (for instance South Mediterranean countries) this principle can even be applied by simply using homeland airbases ...

These estimates set the maximum number of needed systems for ensuring the surveillance of one among the largest countries :

- 8 to 10 airborne systems (3 to 4 loitering ones + ones needed for rotations ensuring long time permanency).
- 3 to 4 associated ground segments (operations plus support).

6.2 A central role in ATBM defense systems

IR HALE UTA systems are not only interesting thanks to the size of the coverage they provide for TBM launch surveillance, but we must underline here the tremendous set of services they can offer in an ATBM defense system :

- In peace and crisis time :

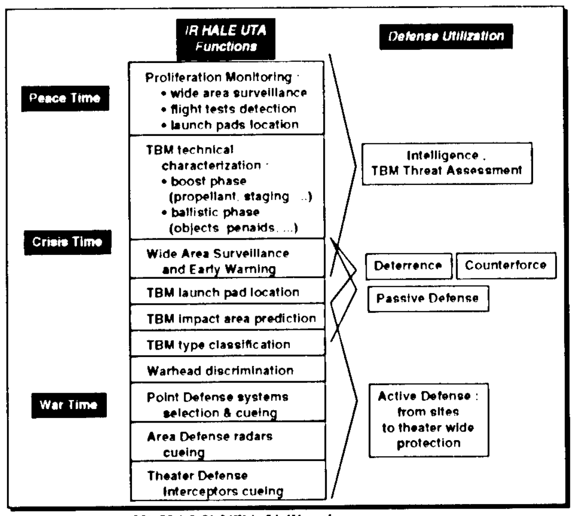
1. Proliferation Monitoring through Wide Area Surveillance of ballistic activity (detection of flight tests in proliferating countries, launch pads location, ...),
2. Proliferating missiles technical characterization : range performance measurement, plume signature measurements, booster staging counting, warhead separation phase analysis, counting and signature measurements of objects present in the ballistic phase (warhead, last boost stage, shroud pieces, separation device pieces, ... that are potential penetration aids into defense system ; intentional penaids ...), ...

   All of this is dedicated both to the characterization of the attacking country's technological level and to improve defense systems readiness in case of conflict

- In crisis / war time :

3. [Quite] Wide Area Surveillance and Early Warning (quite as early as Space-Based systems such as US DSP),
4. TBM launch pad location,
5. TBM type classification / identification (depending on peace time observation campaign measurements and on the dispersion of targets technical parameters),
6. TBM impact area [early & precise] estimate ; the performance level is similar to performances that achievable by radars ; the IR HALE UTA takes advantage of its forward deployment for providing accurate estimates very early,
7. Terminal Point Defense weapon systems [early & precise] selection and cueing,
8. Area Defense Weapon Systems radars [early & precise] selection and cueing, and, in some configurations, direct cueing of Area Defense Interceptors,
9. Theater Exoatmospheric Interceptors direct cueing ; we have to note here that the IR HALE UTA is one of the best solutions for allowing the earliest commitment of such interceptors (especially if they are themselves in forward positions), and thus allowing them to perform the interceptions early in TBM flight (in Ascent Phase, before the apogee) : in such conditions, they can protect tremendous areas,
10. Significant participation in warhead discrimination among all objects present on ballistic trajectories close to one another (see point 2 above) : the IR tracking sensor, maybe associated with additional sensors on the platform that would use other wavelengths, is a valuable means at least for separating heavy bodies from lighter, less emitting ones. This is very helpful for limiting the number of objects tracked and seen as potential warheads by terminal radars, and thus limiting the number of engaged interceptors.

So, while points 1, 2, 3, 4, and (partially) 6 make the IR HALE UTA concept competitive compared with geosynchronous satellite systems as far as technical capabilities are concerned, points 5 to 10 make it clearly competitive compared with radar systems or highly sophisticated Low-Earth Orbit optical systems.



IR HALE UTA Utilizations summary

When we add to this assessment the fact that the estimated acquisition costs seem to be 3 to 4 times lower than those for medium range radar systems or a geosynchronous Early Warning satellite, and at least one order of magnitude lower than LEO satellite systems, the concept becomes really attractive !

6.3 Utilization concept - Comparison with satellites and radars

In fact, this preliminary conclusion has to be balanced against the analysis of «ideal» utilization conditions of each alternative system.

Let's take as first example the comparison between a Space-Based (geosynchronous) IR Early Warning system and IR HALE UTA.

The satellite system's undeniable value comes from the following major features :

- its ability to ensure permanent surveillance over very long periods (years) without any "heavy" ground support,
- the [very large] size of the areas its Field Of View permits to survey,
- its total survivability versus proliferating countries' attack capabilities,
- its absolute stealthiness / discretion which allows its owner to survey any country without being detected.

Let's add as well the following obvious assessment : having its wide Field Of View, the satellite system is a true stand alone surveillance system, whereas the IR HALE UTA requires a preliminary «alert» for being committed on its operation theater : alert coming from intelligence sources, or even directly from activity detection by space-based assets.

All of this underlines in fact the usual special status of Early Warning satellite systems as sovereignty instruments.

Its major limitations lie in the fact that it can observe only TBM boost phase (which leads to poor Impact Point Prediction performance), and only if the burnout does not occur too early : too short range missiles cannot be detected by space-based Early Warning systems.

As far as the radar is concerned, the positioning distinction in terms of utilization concept is less clear, since both systems (radar and IR HALE UTA) may fulfill exactly the same functions in an ATBM defense system. Yet, let's mention the following slight differences :

- a better Early Warning capability for the UTA, due to its flight altitude and its «natural» forward deployment (threat is detected a little bit earlier in its boost phase),
- a more rapid deployment for the UTA (operationally available in a few hours after projection decision versus a few days for the radar),
- the discretion of UTA in its operations,
- the ability to detect very short range TBMs for the radar (their detection by IR HALE UTA is not certain, due to TBM low burnout altitude and the decrease of UTA detection capability when the targets are flying over earth background).
- probably better threat characterization capability for the radar,
- larger adaptation capabilities for the radar in the field of discrimination (thanks to possibilities like waveform adaptation, in real time or day after day in a conflict). In fact, detailed analysis of discrimination function in front of proliferating TBMs should lead us to consider that these two observation systems are more complementary than rival systems, for this function.

7. GROUND SEGMENT AND SYSTEM INTEGRATION

All elements are now gathered in this short briefing for dealing with the question of physical and operational integration into a global defense system.

HALE UTA is both a «classical» UTA in some aspects and a totally non classical one in some other aspects.

Indeed, it is a classical UTA in the sense that :

- it will fly within the atmosphere, the air traffic during climb and descent phases and in consistency with air operations during its whole flight. It is to be developed taking into account all the constraints coming from this environment,
- Its C2 system will have to be compatible with existing or future Air Defense C3I systems in order to be able to give as quickly as possible the right information to the right user.

As for all other concepts (Medium Altitude Endurance UTA, piloted observation aircraft, ...) these two main characteristics have to be taken into account from the early definition phase.

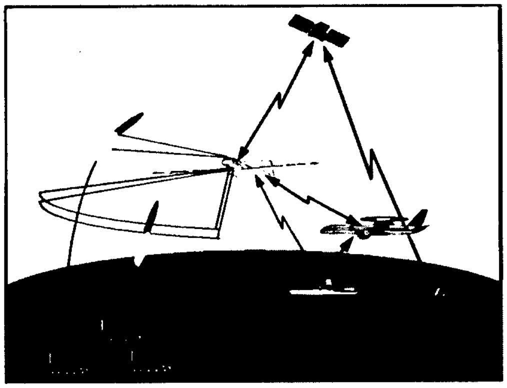
But besides this, two major features make it different from the majority of the other concepts :

- firstly its very long endurance allows patrols with a duration longer than Air Tasking Orders (and moreover all other subsequent, lower level tasking orders) renewal rate : thus the HALE UTA system must be able to respond to inflight retasking, which is not necessary for other surveillance or recce systems,

- secondly, its long projection range and its operation range once projected make it necessary to have several types of links for all ground-to-board or board-to-ground communications links. Data transmission and reception must be achievable :

  - through satellite datalink or airborne relay (other HALE UTA ...) during long distance projection operations, and in surveillance phases when the aircraft is deployed too far from its C2 base : for instance during proliferation monitoring operations such as flight tests detection in peace time, when one does not want to indicate the use of the system, and make it operate from a homeland base. Let's mention here that observation data do not systematically require high rate datalinks, and that the aircraft can be equipped with onboard recorders for peace time intelligence operations.
  - through direct insight datalink. This link is at least necessary in take-off and landing phases, and preferable in climb and descent phases when terrain topography permits it,
  - directly with airborne C3 systems (AWACS airplane, ...), when present, for allowing immediate integration of ballistic events in tactical situation and immediate appropriate reactions.

  Of course, due once more to the UTA long endurance, inflight reconfigurations of these connections must be possible.



Need for various possibilities of links (control & sensor data), depending on scenarios and their phases.

8. HALE UTA OTHER POSSIBLE MISSIONS

Before underlining the major conclusions that we draw from this brief overview of the IR HALE UTA concept (and from longer studies we have carried out ...), we have to highlight that if the TBM launch detection mission requires high operation altitudes, these altitudes are also of major interest in several other surveillance missions.

Indeed, besides the operational advantages (survivability, flight over controlled airspace) provided by these flight altitudes, some missions also take advantage of the wide area covered :

- Ground Surveillance missions :
  - Synthetic Aperture Radar images generation.
  - ground mobile target detection (MTI : Moving Target Indicator).
  - Adverse communications and radar monitoring (COMINT, ELINT).

  Let's note that high altitude often allows higher resolution or target location precision in areas between nadir and observation range than lower (and closer) flying systems, thanks to projection effects ...

- Ground to ground communications relay missions.

Analysis of payload volume, mass and required power supply in such missions shows that they are quite comparable with one another and with IR TBM detection & tracking payload, so that one can envision the possibility of a common generic airplane with removable payload : this would lead to a much higher number of airframes and overall aeronautical segment and thus to a significant reduction in their costs

9. CONCLUSION

The InfraRed High Altitude Long Endurance Unmanned Tactical Aircraft (IR HALE UTA) appears clearly to be a very promising near term solution for fulfilling a large number of needed functions in Anti Tactical Ballistic Missile (ATBM) defense systems.

Placed somewhere between geosynchronous space-based Early Warning assets and TBM surveillance [ground based] radars, they cumulate capabilities offered by these two kinds of systems : early detection of missile plumes like the first ones, and target tracking during their ballistic phase, allowing accurate Impact Point Prediction and handover to terminal intercept Weapon Systems or directly to Theater Wide interceptors, like the latter ones.

Moreover, being easily and rapidly deployed at long ranges as well as being highly survivable they represent an essential surveillance means in peace time, for proliferation monitoring and technical TBM intelligence data gathering.

Being capable of long detection ranges (600 to 8-900 km) like huge ground based radars, they offer large instantaneous surveillance coverage. This coverage remains nonetheless rather limited when compared with geosynchronous satellite systems coverage.

Their technical capabilities are associated to operational virtues related to their high loitering altitude : high discretion and thus high survivability level, flight over controlled airspace, ...

From a technological point of view, all elementary technologies do exist, so that the major challenge lies in system integration

Moreover, their acquisition and operating costs are significantly lower than those of alternative systems : IR HALE UTA does correspond today to a very attractive, cost-effective solution for dealing with Tactical Ballistic Missiles in Out Of Area operations

System Integrity Considerations for Unmanned Tactical Aircraft

D. Scheithauer, G. Wunderlich
Industrieanlagen-Betriebsgesellschaft mbH
Einsteinstraße 20
85521 Ottobrunn
Germany

SUMMARY

In general, unmanned aerial vehicles (UAVs) and Cruise Missiles (CM) have demonstrated their operational value in the limited conflicts of the last years. This experience and technological advances promise similar successful results for more sophisticated Unmanned Tactical Aircraft (UTA) covering a wider range of airborne mission roles [1]. Throughout this publication the term UTA will be used in favour of the term uninhabited combat aerial vehicle (UCAV).

In this paper UTA concepts are evaluated with respect to system integrity. In a first step mission scenarios are analyzed with respect to the hostile threats an UTA will encounter. These external threats together with internal threats affecting reliability and system safety are the reference for the evaluation of the required integrity levels.

On the basis of a generic system architecture essential and non-essential functions are considered. The assessment led to the result that UTA will be quite complex. This will have a major impact on the life cycle costs according to the experience with manned aircraft programmes. However, compared with manned aircraft weapon systems UTA life cycle costs will be lower due to less operating costs.

1. INTRODUCTION

The vision of unmanned airborne systems has a long history. Cruise missiles for attacking fixed targets and Unmanned Aerial Vehicles (UAVs) for surveillance and reconnaissance have demonstrated their operational value in this decade. A common understanding has emerged that unmanned airborne systems may be useful for other operational tasks as well, especially for air-to-ground roles which means heavily defended areas and targets will be encountered. In addition, there is a need to replace ageing aircraft within the next twenty years. The JAST programme in the US and the various studies on future airborne weapon sytems (FAWS) in Europe consider unmanned airborne elements to complement manned aircraft.

Although some airframe concepts are underway, it is still obscure which kind of UTA will offer the best value for money. Will it be an improved cruise missile with additional return to base capability? Or, will it be interchangeable with manned aircraft on a one-to-one basis? What degree of autonomous operation makes sense? Will we have complex automated systems? Or, are simple systems following a 'no avionics' approach better suited?

The answers to these and other similar questions have to be looked at from various perspectives like weapon system performance, handling during the mission and on ground, etc. The viewpoint of this paper are system integrity criteria.

In very general terms system integrity is defined as the capability of a system to fulfil its intended function without unwanted side effects while operating in an environment with specified external and internal threats. From this definition the wide spread influence of system integrity matters is obvious. Therefore, system integrity considerations may assist from early concept studies onwards to assess the required functionality, the necessary complexity and the affordability with respect to available technology and budget constraints.

Starting point is a brief analysis of the mission scenarios for which UTA are promising certain advantages over alternative means. In particular, UTA should survive when they are exposed to the mission environment. Partly for that reason system integrity requirements have to be derived from the mission scenarios. They may have a high impact on the affordability of UTA weapon systems also.

On the basis of UTA functional requirements, key elements of a suitable system architecture will be defined in the next step. The complexity of the individual system functions depends mainly on the degree of operating autonomy and the necessary level of automation. Especially in case of complex functions, system integrity aspects have a far ranging influence on mission accomplishment rates and affordability. A generic block diagram will be presented that is adequate to discuss system integrity further. System integrity will be affected by two kinds of internal threats too:

Paper presented at the AGARD MSP Symposium on "System Design Considerations for Unmanned Tactical Aircraft (UTA)", held in Athens, Greece, 7-9 October 1997, and published in CP-594.

- the susceptibility to random hardware failures and
- the limited capability to design a complex system not only as required (by its specification) but as desired.

From the analysis results from above it will be concluded to what extent operational and system integrity aspects have an impact on the affordability of UTA weapon systems. In addition, the technology areas are defined which need special attention in research and development prior to a successful release of UTA weapon systems to service.

2. MISSION SCENARIOS

2.1 Military Conflicts Characteristics

With the decline of the cold war and the emerging demand for peace keeping and peace making, the mission scenarios have changed. While the planning concentrated on high density conflicts in the past, today adversaries with more or less sophisticated armament have to be considered as well.

As far as relevant for the scope of this paper, in dense conflicts the adversary's potential is characterized by

- high value targets
- high level of reconnaissance and intelligence
- massive air defence en route and at target site
- high level of electronic and information warfare

For peace keeping and peace making missions the potential may vary from case to case. Compared with dense conflicts the following items may roughly indicate the differences:

- high and low value targets
- limited reconnaissance and intelligence
- air defence more concentrated on object level
- varying jamming levels

For out-of-area missions political issues have to be considered as well. The acceptance pilots' losses is extremely limited or may be unacceptable in democratic societies. Collateral damage of own weapons at adversary's sites will also face criticism and may cancel the entire peace-keeping or peace-making involvement. These issues influence the freedom of military commanders to plan and decide according to military needs only and will have a significant impact on the next decades weapon system procurements.

2.2 UTA versus Manned Aircraft

Only two good reasons exist to introduce a new kind of weapon system. Either a specific existing mission can be accomplished more efficiently or a new type of mission is possible providing an advantage over an adversary. So, what are the promises of UTA in this instance? As the name indicates the main difference between current tactical aircraft and UTA is the fact that UTA are unmanned respectively uninhabited. This leads in particular to the following characteristics:

- UTA are not impacted by pilot's fatigue
- By UTA missions no pilot's life is endangered
- The operator's training effort can be reduced because only few real life flight hours are required

The absence of pilot's fatigue allows long endurance and high stress missions. While long endurance missions like surveillance, reconnaissance and intelligence gathering have been successfully accomplished already by UAVs, no weapon delivery role has been performed yet.

Physical and psychical stress to a pilot is mainly induced by the required flight profiles over all mission phases and by the exposure to hostile threats. An UTA is not affected by such limitations.

Due to more aggressive manoeuvring capabilities, advantages would result for a number of mission phases including terrain following, weapon delivery, air combat and defence against incoming hostile missiles. Combined with a long range capability UTA may be used for deep strike missions. Less predictable flight pathes may also enhance the survivabillity in tactical reconnaissance missions.

That UTA losses are not coincident with losses of pilots' lives makes them suitable for dangerous missions with a high loss probability and situations in which human losses are not acceptable for political reasons. In the first case, a high loss probability is likely in dense conflicts with massive air defence of the adversary. The second case is more related to peace keeping and out-of-area missions.

A further reason for the attractiveness of UTA is the envisaged significant reduction of life cycle costs compared with manned systems. In the past several calculations have been performed under various constraints. However, comparisons of manned aircraft and UTA on an equal mission basis (same fire-power, same mission) or with a less capable UTA have led to strong indications of significant life cycle cost reductions. The reason is the small number of training flights required to establish and maintain operators' proficiency. Because the operator will never have the cues of a pilot sitting in an aircraft, there is no difference in

training on a simulator or by real flights. Nevertheless, UTA flights will be necessary to validate the availability of the weapon system, to practise missions performed by a mix of manned aircraft and UTA and last but not least to give military planners and commanders the confidence in their assets.

2.3 UTA versus Cruise Missiles

As far as weapon delivery roles are concerned, Cruise Missiles (CM) are clearly an alternative to UTA. To some extent it is a matter of semantics if UTA should more be down scaled aircraft or up scaled CMs with a return to base capability. For the purpose of this discussion CMs are considered on the basis of today's features. These features are the fire-and-forget philosophy and the existence of one warhead only.

Initially designed for nuclear strike missions, CMs rely on pre-planned missions that are accomplished autonomously. In particular, it is impossible to adjust target data in flight. This limits the flexibility and might be an important risk factor in peace-keeping or peace-making missions, if the adversary tries to provoke hits of non-military assets. The application of CMs is restricted to fixed point targets. Furthermore, the lack of flexibility allows no integrated missions (same target, same time slot) with other flexible means, especially manned aircraft. CMs are best suited to attack high value single point targets that can be destroyed with their limited fire-power. Attacking locally extended targets with CMs is not a cost-effective choice.

Requirements for an advanced CM comprise more flexibility, interoperability with manned aircraft and an increased fire-power. Starting with the first item, increased fire-power depends on the future development of munition technology. Improved explosives and higher impact velocities may offer the opportunity to build smaller weapons. However, these improvements would be beneficial for all weapon platforms.

Flexibility improvements are especially related to the final target acquisition phase. Targeting information may be updated. The CM may be redirected to alternative targets. Or, the attack may be abandoned in the last minute. E. g., in scenarios in which collateral damage should be avoided (peace-making, peace-keeping) a decision relying on on-board sensors may be helpful due to the available resolution of optical and opto-electronic sensors. Real-time updates would also allow missions against moving targets. These could for example be provided by UTA in a tactical reconnaissance role.

A fulfilment of the interoperability requirement is highly related to the flexibility requirement. When command and control of advanced CMs and manned aircraft is similar, combining both types in one mission gives no additional problems.

However, an advanced CM as described above would need sophisticated on-board installations for data transmission and sensing. This will increase CM value and costs. In the end, it may be more efficient to drop the weapon and let the platform return to base. Internal studies performed by IABG at the end of the last decade have shown that the additional development effort for a return to base system is about 10 % to 20 % higher than for a one-way system with the same mission capabilities. According to that study, procurement and operation costs for a whole fleet are comparable with a small advantage for the one-way system. Because these figures were derived a decade ago they should be taken as an rough indicator only. Incorporation of new trends in technology may alter these results.

2.4 UTA Mission Roles

2.4.1 Surveillance and Reconnaissance Mission Types

The first UAV applications were dedicated to surveillance, reconnaissance, electronic support missions (ESM) and jamming. Starting with relatively simple optical sensors, payloads as well as complexity, weight and value of the mission equipment have increased over time. Synthetic aperture radar (SAR) are the most sophisticated sensor equipment used today on UAVs. The potential of current UAVs extends to intelligence gathering as well as to electronic warfare equipment.

A substitution of UAVs in these roles is not expected unless space based systems demonstrate a better value for money. With design concepts for UAVs flying long endurance missions at altitudes of approximately 80 kft, UAVs can operate off-side the combat zone over friendly territory and can still provide useful surveillance data.

In general the mission effectiveness of current UAVs has been demonstrated in low density conflicts like over Bosnia. Despit low reliability records [2], the survivability of the early designs in scenarios with strong air defence capabilities on the adversary's side is questionable. The velocity is low and the flight path simple.

When operating in the combat zone, the measures to enhance survivability include increased subsonic velocity levels, less predictable flight pathes and signature reductions over a wide frequency range. Additional functionality and more sophisticated on-board systems will complement these improvements regarding sensor data processing as well as command and control.

With these enhancements in place, UAVs have all features to evolve to UTA. Due to speed ranges similar to manned aircraft, UTA can be operated together with manned aircraft. More flexible command and control features will support interoperability further. In the end UTA may substitute manned aircraft in the tactical reconnaissance role for a wide mission range. UTA equipped with jammers may assist manned aircraft and other UTA in attack missions.

2.4.2 *Air-To-Ground Missions*

Once concepts for non-reusable attack drones (e. g. TAIFUN) may be anticipated as the first step to air-to-ground missions performed by UTA. Unlike CMs these vehicles participate in the target acquisition process by identifying and selecting targets autonomously.

UTA promoters concentrate on the air-to-ground role due to the following reasons: Improvements of air defence weapons with respect to performance and costs have transformed attack missions to high risk adventures. By the world-wide proliferation of modern air defence systems, attacking aircraft have to expect this threat even in lowest density conflicts. Suppression of Enemy Air Defences (SEAD) is therefore the preferred mission type for UTA. Saturation of the foe's air defence systems by quite simple UTA could be an option. High agility of these UTA with normal accelerations up to 20 g and beyond may outperform most available ground-to-air missiles. Other UTA launching anti-radar missiles may substitute todays similar equipped manned aircraft (e. g. ECR TORNADO, „Wild Weasel" aircraft).

The UTA capabilities for long endurance missions as described above may allow deep strike missions that are less affordable for manned aircraft due to pilot's fatigue. For other typical missions like air interdiction, manned and unmanned aircraft may be interchangeable. It can be assumed that a mix of manned and unmanned aircraft will be the most efficient solution.

However, the availability of a reliable, jam-resistant real-time data link providing the necessary throughput capacity is paramount to accomplish such missions successfully.

2.4.3 *Air-To-Air Missions*

The advantages of UTA over manned aircraft in the air-to-air role are long loiter times and the high g-loads by which most current missiles may be outperformed.

For beyond-visual-range combat, pilots have to rely on identification and flight path data provided by the aircraft systems to perform the manoeuvres best suited to be successful. Remote control and/or automation of this process seems not necessarily more challenging than the air-to-ground roles.

In visual-range combat, transport delays from digital processing limit tracking performance. Unless sampling rates will be significantly increased, manned aircraft will be superior to UTA in this role due to better situational awareness of the pilot.

Advanced concepts assign UTA to Tactical Ballistic Missile (TBM) and CM defence. Such missions evolving in the future are not considered in this paper because the characteristics of TBM and CM defence are only briefly defined today.

2.5 **Offensive Mission Scenario**

Figure 1 shows a schematic overview of an offensive mission scenario for which UTA application is favoured. Assumed is an air interdiction or deep strike mission in a high density conflict situation. The functional elements involved and the appropriate weapon systems are defined in the following subparagraphs.

Airborne Network

Having the right information in the right place and at the right time is one of the key prerequisites to accomplish complex missions successfully. While today's airborne information distribution is centralized around systems like AWACS and J-Stars, modern information technology provides the means to go one step further by providing networks with alternative distribution pathes. Main nodes of the network will be AWACS and J-Star as today complemented by high altitude flying, long endurance UAVs and satellites. Even in dense conflict situations with losses of some nodes survivability of the network will be remarkably enhanced.

The invention of decentralized airborne and space based networks may have other design drivers as well. UTA will profit from the introduction of high capacity and survivable data links. UTA will receive command and control data and will transmit own sensor data and status information. However, the real-time requirements for UTA operation will probably be more stringent than for other tasks.

Command and Control

With the availability of capable networks new options for improved command and control arise. Control of UTA may be performed from ground stations, AWACS aircraft or other manned aircraft preferably those participating in the same sortie as the UTA.

Surveillance and Reconnaissance

In the foreseeable future, surveillance and reconnaissance will be performed by nearly the same means as today. These are manned aircraft, UAVs and satellites. Technological enhancements will shift the importance of satellites. The tactical value of UAVs will be increased by higher operating altitudes around 80 kft.

Electronic and Information Warfare

With the importance of information technology, threats arising from electronic and information warfare will become even more severe than today. Improved defensive as well as offensive measures will be required to sustain the electronic warfare threats. The defensive items will be discussed below together with the system architecture. For offensive measures UTA are well suited to fly ahead of the main attack force with special jamming equipment on-board due to the high risk nature of this role.

Tactical Reconnaissance

With higher quality and higher resolution of remote surveillance and reconnaissance platforms, the demand for tactical reconnaissance may decline. However, its value for final mission preparation and damage assessment will not be surpassed in the near and midterm future. Especially prior to an attack sortie tactical reconnaissance is a high risk mission, making UTA the favorite weapon system to accomplish the mission.

SEAD

For SEAD as the mission with the highest risk UTA may suited best. Two tactical principles may be applied. The first is based on air defence saturation. Easily observable UTA may be used as decoys. Their high agility may outperform the defence missiles while own anti-radar missiles are launched to destroy the air defence sites. The second relies on UTA with low observability launching their anti-radar missiles prior to their own detection by the foe.

Escort

Like today, fighters will escort the main bomber force to provide protection against hostile fighter attacks. As far as beyond-visual-range combat is concerned UTA may participate in this role.

Main Attack

The main attack force has to attack the target with the required fire-power. Depending on UTA size and target characteristics the main attack may be performed by UTA only, a mixed force of UTA and manned aircraft or manned aircraft only.

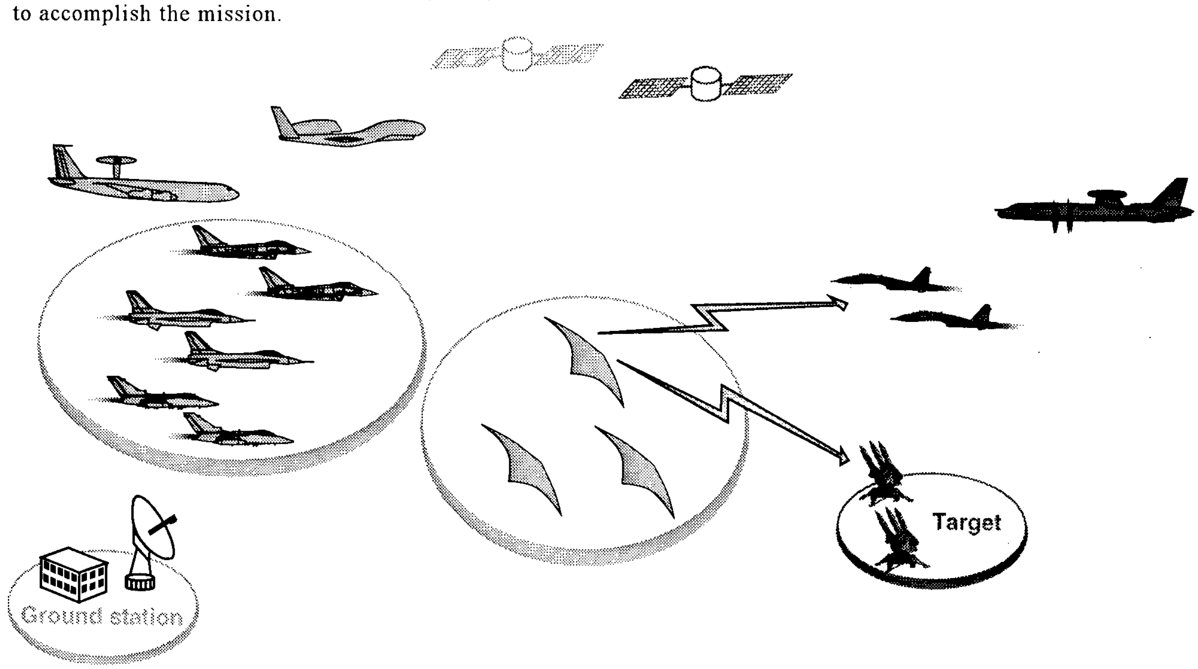


Figure 1: Offensive Mission Scenario.

3. SYSTEM INTEGRITY CONSIDERATIONS

3.1 Threats and System Integrity Requirements

3.1.1 External Threats

For a sufficient integrity level UTA weapon systems have to be designed to accomplish their missions successfully under the constraints imposed by external threats from the mission environment and by internal threats as a result of the UTA system design.

The external threats can be classified by the nature of their origins and severity:

Surveillance, Reconnaissance and Electronic Support Measures of the adversary's air defences

In a high density conflict environment the adversary will have similar means for surveillance and reconnaissance covering AWACS like aircraft, satellites and, depending on the proliferation of those weapon systems, new high altitude reconnaissance platforms. With respect to the networking capabilities, effective usage of the gathered information and the survivability of the complete surveillance system may vary.

Electronic and Information Warfare

In addition to today's techniques for electronic warfare the emerging information warfare technologies have to be considered. Noise input generators to saturate sensors and disturb radio communication links have to be expected in all scenarios. More sophisticated means to manipulate data unperceived by the user may achieve a threat level unknown up to now, on-board information systems have to cope with in future. However, application of these techniques will be limited to countries with the relevant high-tech knowledge.

Anti-Aircraft Missiles

This point comprises missiles launched by aircraft as well as ground-to-air missiles. The availability of very capable modern missile systems to an adversary have to be expected in high density conflicts. The threat may be quite similar in peacemaking out-of area scenarios due to the current degree of proliferation.

Energy Weapons

Although energy weapons play no significant role in military scenarios today, for the future laser weapons and high power microwave (HPM) weapons are likely. If and when they will be available for general use is not foreseeable.

With respect to external threats survivability and vulnerability are the main concerns with respect to system integrity. Survivability describes the capability of a system to withstand the external threats and accomplish the mission. Vulnerability considers the capability of a system to be able to operate after partly damaged.

3.1.2 Internal Threats

Internal threats may be classified in two categories. Expected failures due to random hardware malfunctions may be minimized to an acceptable level by well established technical means (e. g. redundancy, component derating etc). Unexpected events are the second category. They are usually caused by handling problems or design shortfalls. Even for complex systems that are mostly software-based the capability is limited to design a system not only as specified but as desired.

The main system integrity criteria related to internal threats are reliability and safety. Reliability has to be designed in the system so that mission abortion rates are acceptable. It has an impact on the effort of ground handling and maintenance too. Safety as the capability to protect people from death and injuries is clearly an issue for ground handling as it is for manned aircraft, at least due to the carried weapons.

On the first sight, safety during flight seems not to be important because no on-board crew is involved. But it has to be considered that UTA will not operate independently from manned aircraft, neither inflight in civil airspace nor in a combat sortie. Indeed, no own pilot has to be protected, but the inhabitants of adjacent aircraft are endangered by unsafe manoeuvring and unsafe armament system conditions as are people on ground during taxiing, take-off and landing.

3.2 UTA Functional Characteristics

A reasonable starting point for achieving a balanced UTA design is an existing manned aircraft performing the same or a similar task. But a UTA design may not necessarily look like an aircraft. The absence of a pilot removes many design constraints that are imposed for pilot's accomodation. A complete list of these items is quite long. The list includes:

- life support equipment
- controls and displays
- weight and space of pilot and the equipment as listed above
- safe pilot's ejection in case of emergencies
- pilot's physical constraints (g-load, aircraft attitude, other stress factors)

The new design freedom gained by the drop of pilot related requirements shall be utilized to enhance performance as well as integrity of UTA weapon systems. Moreover, it is the most affordable way to acceptable integrity levels when the inherent UTA capabilities are exploited with respect to integrity criteria. In the remaining of this paragraph it will be discussed how UTA design features that are ventilated to the public from various sources affect system integrity.

For the purpose of this consideration the basic functional characteristics are summarized under the headlines airframe, stealth characteristics, flight profiles/agility and UTA on-board systems. While the first three items are considered in this paragraph, UTA on-board systems will be discussed in the next paragraph when the system architecture is introduced.

Table 1 shows a matrix of these functional areas and the external threats. A cross in the matrix indicates that a certain functional characteristic is susceptible to the particular threat. In other words, survivability with respect to this threat may be minimized by appropriate design measures.

Observability by the adversary's surveillance, reconnaissance and electronic support measures is the threat that influences the whole UTA design.

With respect to the airframe, size and shape have a dominant impact on detectability. A small size combined with an appropriate painting scheme contributes to minimum visual observability. In general, UTA may be smaller than manned aircraft. But more than the pilot, the required range and fire-power determine the actual size. To utilize UTA capabilities for long endurance missions the necessary fuel has to be carried. Regarding weapon technology, smart bombs of the 1000 lb range are under development and concepts for new weapons of the 100 lb to 250 lb range with new developed explosives or alternative warheads, e. g. high power microwave (HPM), emerge. Weapon weight and size will therefore decrease being beneficial for both manned and unmanned aircraft. For the near future a substantial reduction in UTA size cannot be expected if compared with manned aircraft on the basis of equivalent fire-power.

To minimize observability by radar, UTA shapes should be chosen that radar echoes are mainly deflected to uncritical aspect angles. A consequent implementation of this design requirement will demand internal weapon carriage. Considering the availability of smaller weapons in future and the internal space offered by flying-wing designs, a successful realization is likely. Depending from the expected threat levels by airborne and ground based radar, UTA concepts showing always the smoothest surface to radar while maintaining the intended flight path may enhance low observability. However, airborne and ground-based radar working on different frequency bands will limit the effect. Other sensor concepts like LIDAR are not affected by such measures at all.

Stealth techniques have the potential to lower the detection probability essentially. But recent experience shows that substantial development is still required to make stealth techniques reliable [3]. If stealth enhancements become available, they are similarly effective against anti-aircraft missiles.

UTA detection by ground based radar can be minimized by chosing terrain following flight profiles. High g-loads allow more aggressive manoeuvring so that the average height above ground will be lower than of today's manned aircraft with terrain following capabilities. Furthermore, terrain following may be maintained over longer time periods.

High agility will be of even more value when an UTA is attacked by anti-aircraft missiles launched from ground or from aircraft. At first, most current anti-aircraft missiles may be outperformed with respect to maximum g-loads. At second, tracking

	External Threats			
	Surveillance RECCE, ESM	Electr. & Info. Warfare	Anti-Aircraft Missiles	Energy Weapons
Functional Area				
Airframe	x			
Stealth Characteristics	x		x	
Flight Profiles / Agility	x		x	
UTA On-Board Systems	x	x	x	x

Table 1: UTA Susceptibility to External Threats.

algorithms of less sophisticated anti-aircraft missiles may be confused due to less predictable flight profiles UTA could perform for their own defence.

The UTA capability for high g-loads that is advantageous regarding anti-aircraft missiles, will be of less benefit against energy weapon attacks.

3.3 System Architecture

Figure 2 shows a generic UTA on-board system architecture that is appropriate to discuss integrity matters. It is common practice to categorize individual functions as essential or non-essential.

Essential functions will perform tasks necessary to survive. Survival covers a minimum capability to return to base. All other safety related functions are essential as well. Loss of non-essential functions will lead normally to a mission abort depending on the mission phase the loss occurred. The ability to withstand external and internal threats may be constrained.

A sound design will keep essential functions to a minimum and will isolate them from non-essential functions.

The minimum set of essential functions covers weapon safety on-ground and inflight as well as basic flight control functions that are required to manoeuvre the UTA safely during take-off, cruise and landing.

For weapon safety, fire control functions and the weapons themselves have to be designed to fulfil the applicable safety requirements. As derived above, these safety requirements are identical with those for manned aircraft. Relaxations would only be granted for the unlikely case that operators will accept higher risk levels in future than today.

Essential flight control functions comprise flight and engine control including sensors, computing ressources and actuation as well as the engine and the control surfaces. The sensors used shall be passive with respect to the environment. Navigation will probably be based on GPS and inertial platforms.

Electrical power generation and cooling equipment is essential in so far that the supplies of essential functions are maintained. With advances in research to substitute hydraulic actuation by electrical means the need for a hydraulic system may diminish.

Even if not completely, to some extent the data link

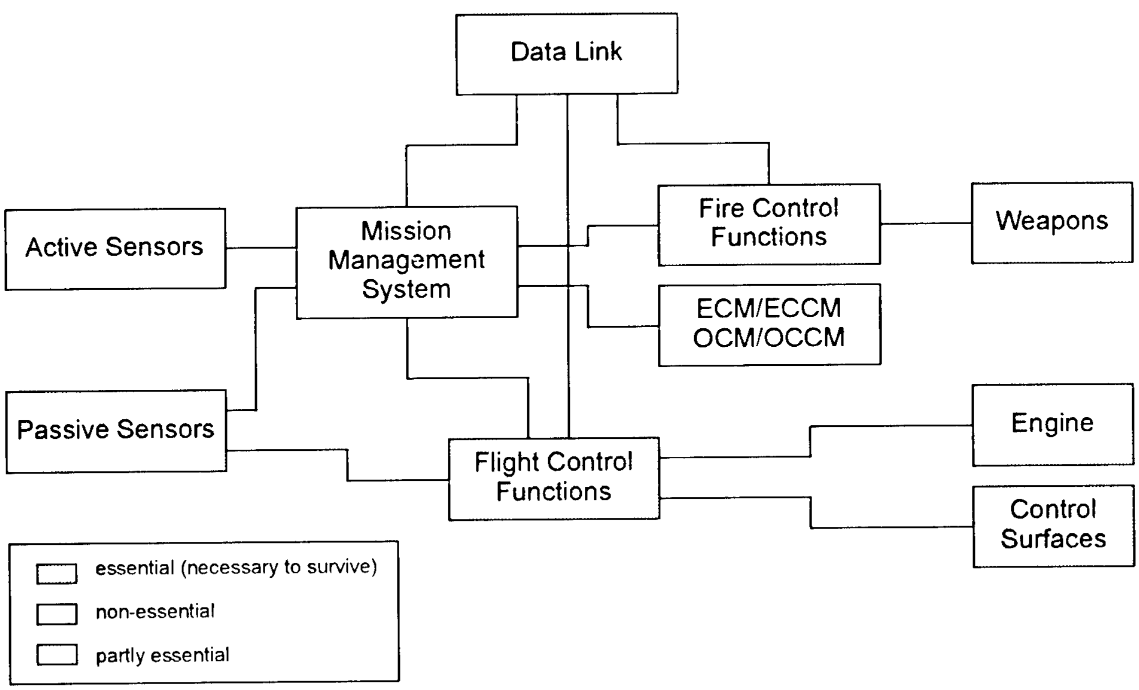


Figure 2: UTA System Architecture.

will be essential. Depending on the degree of autonomy of essential functions, uninterrupted performance of the data link may not be demanded. However, the information integrity of the commands transmitted to release weapons or initialize aircraft manoeuvres has to be ensured. The requirements on data link availability will be considered further below when the susceptibility to external threats will be discussed.

Due to the importance of the communication between UTA and a remote controller, the data link will directly exchange data with the essential functions for two reasons: safety relevant information must not be routed via non-essential functions and real-time requirements may demand minimization of transport delays. The mission management system comprises all mission relating computing. For a specific application the mission management system will likely be refined to subsystems that themselves may be related in a hierarchical fashion. The function included cover at least:

- signal processing of sensor data input from passive and active sensors
- threat evaluation and countermeasures
- mission dependent guidance command processing for fire and flight control
- concentrating information to be sent to the remote controller for maintaining situational awareness
- health monitoring and status accounting to be transmitted to the remote controller and to be used on-board for reconfiguration

In the following the on-board systems will be further evaluated with respect to their susceptibility to external threats. Table 2 provides an overview. It shall be interpreted in the same way as table 1.

In principle all antennas are susceptible to detection by the adversary's surveillance and reconnaissance systems or by electronic supporting measures, especially when transmitting. Therefore active sensors should not be operated in continuous modes but only when operationally required. Onboard radar for example may only be used for final target acquisition.

Electronic and information warfare attacks are a major threat for all electronic devices. Noise and manipulated data can be induced to the on-board systems via all systems that interact with the outside world. These systems are active and passive sensors, the data link and the own electronic warfare suite. Although countermeasures from the own electronic and information warfare suite may augment severity and duration of such attacks, system architecture and design features of each individual system have to complement the defence. The principles for defence include hierarchical protection concepts, dissimilarity and redundancy. Comparable information on the environment should be gathered by several sensors based on different sensor technology and working on different frequency bands to counteract noise generation and decoys.

The data link should consist of redundant broadband communication channels to lower the probability of a total data link breakdown in case of induced noise. However, it is unlikely that the datalink will operate without timely limited disturbances not only caused by electronic warfare but also as a result of geographical conditions or meteorological anomalies. Consequently, continuous data transmissions with high real-time requirements should be avoided. Instead, all time critical functions should be processed on-board autonomously. Data encryption methods and redundant distribution will protect the information from being understood by the adversary and from being manipulated without detection.

Input processing of all systems interacting with the environment shall be used to detect corrupted data and to serve as a firewall for all other systems. Essential functions should not rely on data that has a high potential to be corrupted. The absence of pilot's interfaces on-board allow shielding concepts that enhance isolation of essential functions from the outside world by concentrating the equipment in completely shielded compartments.

With respect to anti-aircraft missiles active sensors and transmitters of the electronic warfare suite are susceptible. Guided by a home-on-jam mode, missiles will utilize the radiated energy to find their target. A capability to switch of the transmitters without a significant impact on mission execution and electronic countermeasures will reduce the severity of the threat.

Energy weapons may become a severe threat in the future. Although the effect is different from electronic warfare, the principles for protection against energy weapons are similar.

Conclusively, the countermeasures against external threats for UTA have a lot in common with what is applicable to manned aircraft because of similar requirements on many on-board systems. Therefore, it makes sense to identify and summarize the differences:

- The reliance on the data link is higher in case of a UTA although effectiveness of manned aircraft is also more and more dependent from the networking capabilities. Especially, strong real-time requirements on the data link makes UTA susceptible to jamming.
- Shielding of UTA on-board systems will achieve a better protection level against electro-magnetic interference caused by electronic warfare and energy weapons.

3.4 UTA Affordability

The requirement for a new kind of weapon system is justified if the following criteria are met satisfactorily:

- New mission types can be executed that are required with respect to operational needs and that cannot be performed by current weapon systems, or an existing mission type can be executed more reliable.
- Operational handling requirements imposed by the weapon system are adequate with respect to the environment and people's skills.
- The technology is available or can be invented with reasonable effort.
- The new weapon system is cost-effective.

The first item was discussed in depth above. With respect to operational handling, recent experience from UAVs was troublesome [2]. The required ground support exceeded the expectations. Low reliability records have led to a maintenance effort that exceeded acceptable levels. Furthermore, other systems may be endangered by operating UAVs. For example, shipboard operation of UAVs may be unfeasible in practice. Therefore, reliability improvements are required prior to fielding UTA weapon systems.

Regarding technology manned aircraft design practices offer a sound basis to start a UTA development. UTA will probably benefit from further technological achievements in manned aircraft design, information technology and weapon technology. However, most of this technology is expensive and ongoing research and development effort is useful to provide the same functionality for less costs.

In some areas technical requirements are more stringent for UTA than for manned aircraft. In these cases UTA concepts have to drive research and development:

- UTA specific airframe performance characteristics have to be analyzed

	External Threats			
	Surveillance RECCE, ESM	Electr. & Info. Warfare	Anti-Aircraft Missiles	Energy Weapons
UTA On-Board Systems				
Data Link	x	x		x
Active Sensors	x	x	x	x
Passive Sensors		x		x
Mission Management System		x		x
ECM/ECCM/OCM/OCCM	x	x	x	x
Flight Control Functions		x		x
Engine			x	
Control Surface Actuation				
Fire Control Functions		x		x
Weapons				x

Table 2: UTA On-Board Systems Susceptibility to External Threats.

- Reliable data links on the basis of networking technology that provide excellent survivability (even for functions with strong real-time requirements) have to be invented.
- Allocation of data processing within the network has to be defined and optimized.
- Control strategies to manage complex on-board systems autonomously have to be defined utilizing neural networks and other artificial intelligence techniques.
- Advanced concepts for remote control have to be invented considering control tasks, real-time requirements etc.
- Techniques to enhance system integrity have to be developed. In parallel, the costs to implement high integrity systems should be significantly reduced.

Finally, life cycle costs of UTA have to be discussed. From the results of this survey it is concluded that UTA will have to provide a high integrity level. This will severely influence the complexity of on-board systems. Particular systems will have to provide adequate redundancy levels to meet overall system integrity requirements with respect to reliability and safety. Without technology improvements in the relevant areas, integrity requirements will drive development costs to a similar level as for manned aircraft.

Procurement costs of UTA weapon systems will be similar to manned aircraft weapon systems. However, if the capabilities of one UTA, with respect to achievable fire-power and the loss and sortie rates will be at an optimum, procurement cost may be lower compared with an equivalent manned aircraft fleet. Because UTA airframes will be designed for less flying hours this will also contribute to lower procurement costs.

The real cost benefits of UTA are related to operating costs. Basic flight training of UTA controllers can be performed in a simulation environment. Hence the need for actual flying hours will be reduced. Most UTA could be in protected storage while a small number is used for check and demonstration flights as well as for tactical training in case of missions to be flown in a mix of UTA and manned aircraft. This concept requires improvements of long time storage techniques and solutions to gain the necessary maintenance experience. However, military commanders have to get confidence in the capabilities of their weapon systems by training in real world situations. The actual demand of flight hours for this purpose is uncertain.

4. CONCLUSIONS

This paper dealt with system integrity of future UTA weapon systems and the impact on design and affordability. In dense conflicts UTA weapon systems will be used primarily for high risk and long endurance missions, e. g. tactical recconnaissance and SEAD. In lower density conflicts like peace-keeping missions UTA may perform for which the public may not accept pilots' losses.

High integrity is required to withstand external and internal threats in an offensive mission scenario. Especially, the data link is critical to provide real-time control. Safety has to be considered with respect to weapons and flight path control. UTA have to be reliable to minimize the maintenance effort. Consequently, UTA on-board systems will be quite complex.

At all, a UTA will be more similar to a manned aircraft than to an improved cruise missile with a return-to-base capability. UTA development costs will be similar as for manned aircraft. Procurement may be slightly lower. Cost-effectiveness of UTA will be based on essentially lower operating costs than for manned aircraft.

Furthermore, technology areas have been defined which for further research and development is recommended before a dedicated UTA development program should be launched. Among others, system architectures as well as design and verification methods have to be developed to provide cost-effective implementation of high integrity levels.

REFERENCES

1. AGARD: Aerospace 2020, Volume 1 - Summary. AGARD Advisory Report 360. AGARD, Neuilly-sur-Seine, 1997.

2. GAO: Unmanned Aerial Vehicles - DODs Acquisition Efforts. Washington D.C., 1997.

3. GAO: B-2 Bomber - Cost and Operational Issues. Washington D.C., 1997.

JOINT SEMI-AUTONOMOUS AIR WEAPON SYSTEM

R. W. Schwartz
S. B. Millett
Systems Engineering Division
F. T. Rogers
B. Hedman
Concept Analysis and Evaluation Department
Naval Air Warfare Center, Weapons Division
China Lake, CA 93555 USA

SUMMARY

The Naval Air Warfare Center has investigated the idea of a semi-autonomous air weapon system that could be used in a lethal role. While such a system appears to be a natural continuation of military aviation we are just now beginning to appreciate some the nuances inherent in such a system.

In our approach we will not just "put weapons on UAV" or "take the pilot out of cockpit" either physically or mentally, or produce "more capable one-time use weapons." Rather our proposal for JSAAWS is for a total weapon system designed for the tasks at hand.

There are two lessons to be learned from history. The first lesson is that a new weapon concept such as JSAAWS must be designed for its intended application and not be just a retrofit of an existing system. The second lesson is that we need to develop JSAAWS in an orderly fashion, we need to walk before we run.

Potential advantages of a JSAAWS for a Naval Expeditionary Force include increased survivability, decreased cost, increased lethality, via increased OPTEMPO and the ability of a JSAAWS to act as a force multiplier, and the ability to show a more aggressive presence when first-on-the-scene.

In whatever role it plays, JSAAWS must be cost effective when compared to manned aircraft and one time use 'smart' weapons. One major contributor to cost savings would be greatly decreased operations and support costs due to vastly decreased flying hours. For example, life cycle cost could be reduced by 28% just from reduced flight hours.

We have looked at several missions for a JSAAWS, some of which are more suitable for a JSAAWS then others.. These are: SEAD (the initial mission of choice for the operational community), Battlefield Support / Simplification, Armed Recce, ASuW in the Littoral, supporting Operational Maneuver...from the Sea, Counter Cruise Missiles, Offensive Counter Air, and Defensive Counter Air.

Three notional system design concepts have been defined that cover all of the missions for a Naval Expeditionary Force. The high-end concept is the Highly Maneuverable Lethal Vehicle, which will be described in detail in paper 4 of this Conference. This would be a multi-role system for both air-to-air and air-to-surface missions. The air arsenal ship is a concept that has been put forward by the US Air Force. It would have limited air-to-air and air-to-surface roles. The low-end concept would have capability in a limited, but operationally significant, set of air-to-surface missions, CAS, BAI, AI, SEAD, Indirect Fires. Included in this mission set is a significant percentage of the total targets for tactical combat aircraft.

1 INTRODUCTION

Over the past several years there has been steadily increasing interest and activity in the area of pilotless systems that could do more than surveillance. These putative systems have appeared under various names: Weaponized Unmanned Air Vehicles (WUAV); Tactical Unmanned Aerial Vehicle (TUAV); Unmanned Tactical Aircraft (UTA); Uninhabited Air Vehicles (UAV), where the term uninhabited means unmanned but still controlled to some degree from outside the cockpit; Lethal Unmanned Vehicles (LUV); Lethal Uninhabited Combat Air Vehicles (LUCAV); Unmanned Aerial Vehicles (UAV, again); Unconstrained Maneuvering Air Vehicle (UMAV). The constant thread here is that the system is defined by what it is not, i.e., not manned by a pilot.

This situation is analogous to that which developed when the automobile was first in use. When the automobile was first invented it was called a horseless carriage, as this was the only way to describe its essential quality, i.e., it carried things over land without a horse. The automobile is much more than a carriage without a horse, it is much, much more. However it could only be described in the reference frame that existed, and in that reference frame it could only be described at the time by what it was not. The same thing is true for JSAAWS, at the moment we describe it by what it is not.

While this is as much a matter of semantics as anything else, words do carry with them meanings. Thus to call the system unmanned or uninhabited carries with it the definitions that people have given to these words in this context. We could try empty or vacant, but that would give rise to entirely different pictures, so we go with joint semi-autonomous air weapon system (JSAAWS). It is difficult to describe something completely new using words that bring with them pictures and ideas from

Paper presented at the AGARD MSP Symposium on "System Design Considerations for Unmanned Tactical Aircraft (UTA)", held in Athens, Greece, 7-9 October 1997, and published in CP-594.

existing things.

We believe at this time we can start to define an uninhabited system by what it is rather than by what it is not. The primary attribute of this concept is that it is to be designed and built using a weapon philosophy. This differs from the approaches currently used to produce aircraft and UAV. Explicit details on what this means will be given later. The major difference between this concept and current 'smart' weapons is that the most expensive part of this weapon system is recoverable and reusable. We do believe that when executed correctly this approach will provide a discontinuous change in the way we fight. It will be a jump ahead.

Possible mission roles are being developed for JSAAWS. The fundamental idea behind such a system is to maximize the survivability of pilots and optimize the system cost effectiveness, by providing the option to use a cost effective JSAAWS instead of a manned vehicle, or a one-time use 'smart' weapon such as a cruise missile, thus allowing pilots to avoid the most dangerous, dull, and dirty parts of the battlefield, yet retain the real-time tactical mission flexibility that is the hallmark of TACAIR.

There are several trends, that taken together, are drivers for initiating a study of such a concept now. Defense budgets are likely to continue to decrease, or at best remain uncertain, over the next several years. The Naval Services and the rest of the DoD will continue downsizing. While this trend continues it remains a matter of national security to maintain, or increase if feasible, our capabilities. Whatever we do, threat spectrum we face is becoming increasingly lethal and widespread. At the same time, particularly in conflicts that the American people do not see as directly related to our national survival, public tolerance is decreasing for any casualties, military or civilian, hostile, neutral, or friendly.

Any solution to this problem must be cost effective relative to alternative approaches, and must integrate with and the existing/proposed force structure.

Our approach has been to look in an iterative fashion at valid mission roles, general issues and requirements, notional operational concepts (at the mission and engagement level), and notional implementation concepts.

We have identified several general issues that must be addressed before a JSAAWS can be considered for operational use. Flexibility to retarget is important, as is positive combat identification (PCID) of ground targets. It will also be important to have well defined rules of engagement (ROEs) for accountability, and an over-ride capability to maintain positive control. Finally, it will be critical to establish operational doctrine for cooperative engagement with manned aircraft and other joint, coalition and allied forces. The JSAAWS must be integrated into the general communications network and contribute to overall battlespace awareness.

We have made one complete pass through these four areas and this paper and presentation report the results of that activity. At this point we have no single notion of what a JSAAWS should be. Rather we have a collection of ideas about different aspects of this system, some of which appear to be contradictory. However, as each iteration refines the thinking about these areas, we will pursue additional subjects, including technical and operational issues and technical deficiencies which can lead to investment decisions. We will also investigate the current state of technology and determine what demonstrations are both feasible and necessary. We plan for these later activities to lead to maturation of one or more specific concepts and the technologies required to implement them, and finally to development of the system.

2 LESSONS OF HISTORY

The JSAAWS concept is a natural evolution of trends in military aviation. Because of the ever-increasing pilot workload, one trend is that more and more functions on aircraft are being performed without the intervention, or in some cases even without the initiation, of the pilot. On the weapon side, the trend is toward more and more autonomy and multimission roles. Walleye, at the state of the art 25 years ago with its datalink and MITL guidance, can be compared to Tomahawk, with its long range and preplanned strike capabilities. The notional next step will expand the role of the weapon even more. A third trend is the proposed evolution of UAVs from unarmed reconnaissance to armed combat. These trends converge to a weapon system, or more likely, a family of weapons systems. It is in the space of this convergence that we want to look for concepts for JSAAWS.

Moving to a JSAAWS also continues the general trend in military aviation, and we can see history repeating itself.

When manned aircraft were first used, both for over-land and at-sea operations, their purpose was surveillance and reconnaissance. Commanders wanted to know where the enemy was and what they were doing. This was the equivalent of taking the high ground for information purposes so that maneuvers could be more effective. This is the current operational status of UAVs. We use them to locate troops and other potential targets. For manned aircraft this evolved into serving as spotters for artillery and naval gun fire. In addition to locating targets and providing that information to the gunners, manned aircraft could also feed back better information on where shells were landing and more rapidly correct firing solutions. They served a targeting and fire control function. UAVs are being used in that manner today, in

support of field artillery. There is currently a lot of discussion, and some experimentation, using off-board assets to provide real-time-information-into-the cockpit (RTIC) and to designate targets using lasers.

In the history of manned aircraft, he next step was to incorporate on-board ordnance. The original ordnance was not very effective nor were the aircraft effective at delivering it, because neither had been designed and built for that purpose. This application for unmanned systems is also generating a lot of discussion and some experimentation. There are reports of one or two experiments in the Army and Marines using UAVs to drop bombs and shoot missiles.

The final mission step for manned aircraft was to deliver ordnance. This also led to the need to survive attack, both from other aircraft and from the ground. As the purpose changed so did the designs.

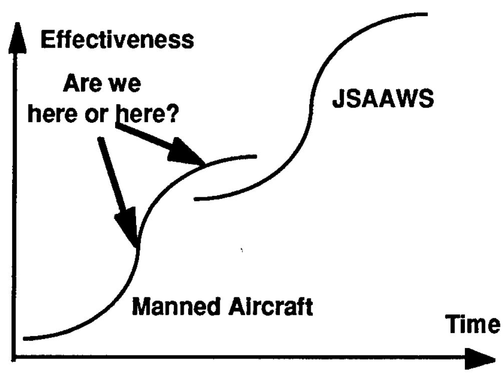
There are two lessons to be learned from this history. The first lesson is that a successful, effective JSAAWS must be designed for its intended application and not be just a retrofit of an existing system. The second lesson is that we need to develop JSAAWS in an orderly fashion, we need to walk before we run. As in any endeavor, when we try to change too many things at once we usually don't succeed. Thus we need to take a step-by-step approach and not try to do too much at first with JSAAWS. This ensures that any mistakes we might make don't cost too much because corrections are easier to make. But it also means that to have any significant capability when it is needed we need to start activities now.

One fundamental question that will be answered in the next several years is which way will we go with unmanned systems? Will we learn the lessons of history or not?

The notion of a JSAAWS, or something similar, is not new. There are numerous examples of unmanned vehicles carrying and releasing weapons going back many years. So we must ask ourselves two questions. Why should we be thinking about moving from manned aircraft to JSAAWS? and What is different now that makes us think we are ready to do this successfully on a routine basis? The answer to the first lies on the typical technology "S" curves shown in Figure 1.

If we think we are still on the steep part of the curve for manned aircraft then it will be more cost effective for us to continue to develop them . If we think we are on the flatter part of the curve then in order to make significant improvements in combat effectiveness we are going to have to leave the manned aircraft curve, even if the initial JSSAWS are somewhat less capable.

Figure 1. Technology Maturation Curve



Several technologies contribute to the ultimate success of a JSAAWS. The primary technology is the Global Position Satellite (GPS) system. This system allows both extremely accurate navigation and weapons delivery to a determined location to be automated to an extent that has not been possible in the past. The ability to control air vehicle flight via computers has been demonstrated in a number of "fly by wire" aircraft. This, coupled with the huge amount of computing capability that is available from modern signal processors and advances in intelligent decision making algorithms will allow these systems to fly themselves given only upper level commands.

3 UTILITY

Potential advantages of a JSAAWS for a Naval Expeditionary Force could occur in several area. These include, decreased casualties, increased survivability, decreased cost, increased lethality via increased OPTEMPO and ability of a JSAAWS to act as a force multiplier, and the command option to show a more dominating presence when first-on-the-scene. Below we postulate several possibilities, each of which is dependent on the JSAAWS having the increased capabilities specified. Which of these is attained will depend on what specific implementation, or implementations, of this concept actually come to fruition.

The ability to put an opponent's assets at risk in situations that would otherwise be highly dangerous for our warriors greatly increases the acceptable tactical and strategic options available to our commanders, both in limited warfare environments where loss of American warriors' lives is unacceptable, and in high-tempo warfare, where skilled pilots are an asset that is not replaceable in the near term.

In addition, the training required for such missions carries its own hazards and losses. Pilot survivability in training mishaps ensures their availability when needed

for combat.

OPTEMPO and force multiplication could be increased in a number of ways. Being pilotless, time on station would be determined by hardware issues such as refueling capabilities and mean flight hours between operational mission failure (MFHBOMF). On the ground, turn-around times might be decreased if there were no sub-systems devoted to the pilot. If JSAAWS is used in CAP-like missions then pilots can be more available for missions that require human presence. Using a JSAAWS could reduce the need for SEAD, because, depending on design specifics, its unmanned nature could allow much more aggressive and survivable nap-of-the-earth ingress, or it could be smaller and less observable, or it could out-maneuver threat missiles, or any one of a number of other attributes could lead to greater survivability against threats. This would allow urgent targets to be attacked as needed, and SEAD would be performed only when needed, such as before manned aircraft are used in a particular area. A highly survivable JSAAWS that could get in close enough to the target and had adequate flight control, weapons release capability and targeting information could use abundant, simple ordnance, such as guns, rockets, and dumb bombs. This would mean that weapons will always be available.

Decreased cost of ownership is possible from a number of aspects. There will be no cockpit or life support systems. This leads to a direct cost saving and, because of the decrease in weight, to a further indirect savings. Because the airframe will not have to be man-rated the amount of safety margin required will be decreased, which in turn will lower manufacturing and O&S costs as well as decrease test and evaluation costs. In addition if we think of the air vehicle as just another subsystem we could look at balancing the cost of maintenance vice that of replacement. This would mean building the air vehicle for finite use rather than as the longest lived subsystem, and then replacing it if it is cost effective to do so.

One example of how operation and support costs might be reduced is that of flying hours. One option would be to build the vehicle for a pre-selected number of flight hours. If we choose 1,000 flight hours as the total we can get significant cost savings. Let us assume 800 hours combat and 200 hours training. This 1,000 flight hours is roughly one-eighth the number of flight hours, takeoffs and landings as a typical F/A-18. We further assume savings accrue as a *pro rata* percentage of total program cost and use the life cycle costs (LCC) data generated by the Joint Advanced Strike Technology program.

From procurement we have a savings of 7/8 of the cost of initial spares, which is 2% of the LCC. This gives a 1.8% LCC savings. From operations and support (O&S) we have a savings of 7/8 of the cost of unit level consumption, maintenance, and support. This has been calculated to be 30% of the LCC, which leads to a savings of 26.2% of LCC. Note that this savings comes from the peacetime O&S costs, traditionally the most difficult funds to obtain. Taken together these give a life cycle cost savings of 28% just from reduced peacetime flight hours. Additional savings could also be available from reduced unit procurement costs and possibly from reduced manning levels and base support for training. The unit procurement costs need to include the cost of ground stations supporting the JSAAWS; one unresolved issue is the number of JSAAWS that could be supported by each ground station.

Other potential sources of overall system cost savings include: a JSAAWS, because of its inherent survivability, would also not require a large strike support package and the number of support aircraft could be decreased; most training could be performed by simulation decreasing training costs beyond just those from decreased flight hours - for example we would no longer need to build flight trainers; increased survivability could also allow the use of shorter range, less expensive, expendable ordnance such as guns, rockets, and dumb bombs. Higher lethality, because of increased weapons delivery accuracy, also means that less ordnance of any type would need to be used on any target.

Other areas of potential cost savings that will need to be investigated include a decreased logistics footprint and a decreased support infrastructure, including the possibility of decreased manning levels.

A JSAAWS will allow a Naval Expeditionary Force (NEF) to have a much more aggressive presence when it is first on the scene, or at any time. The NEF will have limited assets, typically one carrier battle group, yet in the early stages of a crisis or a conflict that erupts suddenly it might have to carry out the full range of missions. Also because by definition we are trying to bring the fight to the enemy, our adversaries will either be within their own borders or just across from them. Thus, in addition to interior lines of supply, they will have access to their entire stockpile of assets, all of which we may not know about, either their location or their capability. Also, at least at first, we are likely to be in a reactive mode because an adversary's intentions might not be fully known.

Because there is no danger of casualties a JSAAWS will allow us to fly against an unknown adversary as one way to assess his strength and intentions. Using it aggressively will also allow us to impact the outcome early on in either a Forward Presence/Crisis Response situation or in the first days of a campaign.

One caveat to this is that in the early days of JSAAWS incorporation into the Force Structure we are likely to be as cautious of their use in high risk situations as we are now with manned aircraft or current UAVs. As an

important asset, the loss of even one would be a serious consideration. But if we can change the mindset then we can move to a more liberal use of these systems.

4 CHANGE THE MINDSET

In our approach we will not just "put weapons on UAV" or "take the pilot out of cockpit" either physically or mentally, or produce "more capable one-time use weapons." Rather our proposal for JSAAWS is for a total weapon system designed for the tasks at hand.

One thing that needs to be done to maximize the benefit of a JSAAWS is to break out of our old ways of thinking about aircraft and weapons from both an operational perspective and in the engineering design.

Operationally we need to think about using a JSAAWS as if it were a weapon and not an aircraft. This new approach means that operationally mission lines can blur when we consider how to use a JSAAWS. New missions can also be considered, and old missions that were abandoned for various reasons can be reconsidered. In this context JSAAWS changes the calculus of attrition, survivability becomes strictly an economic and warfighting effectiveness issue, not an issue of casualties. This, coupled with the postulated increased capabilities of a JSAAWS, allows us to look at new tactics for its employment. It also allows us to look again at older tactics that have lost favor because of survivability concerns.

On the engineering design side we need to stop thinking of JSAAWS as aircraft or a UAV and start thinking in terms of a weapon system. To build such a system might require us to combine the expertise of those who can cost effectively build re-usable vehicular platforms with those who can design and build weapons that work the first time, even after many years of storage.

We need to get around our notion that aircraft break if they are not used and to think "All Up Round" for a JSAAWS. Since most will not be in peacetime use, but need to work the first time out of the box during hostilities, we need to be concerned from the first with designing in total system reliability, and to back that we need built in tests (BITs) that check a greater percentage of probable potential failure modes, compared to manned aircraft.

Another example - aircraft have tops and bottoms and sides, but should a JSAAWS? And if it does have a top, bottom and sides, should the inlet go on top to mitigate signature issues, and should the ground looking sensors go on the bottom? While just the opposite of manned aircraft, these may be the best JSAAWS system solution.

Another option is to missionize JSAAWS so that it carries only what it needs for a specific mission. Make all subsystems "Plug and Play", and make the Air Vehicle just another subsystem. Look at balancing the cost of maintenance vice that of replacement. Think about building the air vehicle for finite use rather than as the longest lived subsystem, and replace it when it is cost effective to do so. These and several other considerations are shown in Table I.

Table I. Aircraft - JSAAWS - Weapons Comparisons

Aircraft	JSAAWS	Weapons
High value asset	Capable, reusable ultimately expendable	Expendable
Pilot in vehicle Non-autonomous	Operator not in vehicle Semi-Autonomous	No operator Autonomous in free flight
Requires constant maintenance	All-up-Round, but Maintain during combat	All-up-Round
Build to maintain Multiple flights (~8,000 hr)	Build to replace Multiple flights (~1,000 hr)	Build to use once Free flight (~2 hr) Many captive carries
Air Vehicle primary subsystem - 70% unit cost	No primary subsystem - cost and capability uniformly distributed	Guidance & Control primary subsystem - 60% unit cost
Training/proficiency flights >95%	Combat flights ~80%	Combat flights ~ 95%
Fly to retain pilot proficiency	Fly to retain maintenance proficiency & check system readiness	Fly to check system readiness
Unit cost $30M-$80M	Unit cost (goal) <$10M	Unit cost <$1M
O&S unit cost $30M-$80M	O&S unit cost (goal) <$5M	O&S unit cost 20% unit cost

What we are trying to capture here is the idea that traditional military aircraft are built to do a lot more than deliver ordnance. In fact their primary function is to bring themselves and the pilot (both valuable, scarce assets, back to the ship. Typical survival probabilities for manned aircraft in combat are greater than 0.998 per

sortie, while typical probabilities of killing a target for the same aircraft are less than 0.5 per sortie. Compare this to a JSAAWS that has as its primary function delivering weapons on targets. Thus we need to be weapon delivery centric in our designs rather than pilot centric.

This means that certain subsystems can have different requirements depending on whether they are being used in the air vehicle mode or the weapon system mode. In some cases not only are the requirements different, but entirely different data are needed by the two systems, air vehicle and weapon system. In general for a JSAAWS weapon system, requirements will be more stringent then air vehicle requirements. Take as one example the navigation system. In an aircraft (air vehicle) the purpose of this system is largely to get from point to point and the horizontal position only needs to be known to within hundreds of meters, while for a weapon delivery system this needs to be known to within meters. For vertical position aircraft use barometric pressure, which is good to within tens of meters, while the weapon system needs this to within meters. Aircraft normally need to know ground speed to within 2-4 km/hr, while a weapon system needs this information to within cm/sec.

Both the uninhabited aircraft and the armed UAV have their proponents. Our view is that if one or the other of those approaches is the only one taken then we will be, in effect, limiting our options before we even start to look at the issues. Each of those approaches has an existing community and an existing mindset, not to mention existing hardware, that it will bring to the table. If the implementation is simply bringing together existing components, i. e., existing weapons and platforms, then it might be available quickly, and would be valuable for initial looks at the operational issues involved in fielding such a system, but such an implementation will not be an optimized system and will not take full advantage of the concept either in performance or affordability. To maximize the benefit in terms of cost effectiveness of JSAAWS we need to break out of our old ways of thinking about aircraft and weapons from both an operational perspective and in the engineering design.

5 MISSIONS

We have looked at several missions for a JSAAWS, some of which are more compatible with a JSAAWS then others. These are: SEAD, Battlefield Support / Simplification, Armed Recce, ASuW in the Littoral, supporting Operational Maneuver...from the Sea, Counter Cruise Missiles, Offensive Counter Air, and Defensive Counter Air. Our initial thoughts for these missions are presented below.

SEAD. This is the initial mission of choice for those elements of the operational community with whom we have discussed this concept. A survivable JSAAWS, as postulated above, increases the options to do lethal, non-lethal, or no SEAD. The threat/target can be attacked from multiple directions. Non-lethal options are similar (but not identical) to those for manned aircraft; cheap disposable jammers, chaff delivered in more flexible corridors or directly over a radar, self jamming where decreased range allows for smaller power/aperture. Lethal options include using cheaper, general purpose weapons. Because of the potential for nap-of-the-earth flight, decreased size and observability and increased maneuverability, JSAAWS will also be more survivable against pop-up SAMs. This allows JSAAWS the flexibility to ignore air defenses, if the pre-briefed mission is time critical or to attack them if not.

Several employment tactics have been considered. Terminal evasion and very low level (~50 ft.) flight are two that look attractive. The continuous threat of attack by a nap-of-the-earth JSAAWS will drive threat radar to be on more making them vulnerable to HARM attack. The net result is that SEAD changes from a requirement to an option.

Battlefield Support/Simplification. This is a combination and evolution of Close Air Support (CAS), Battlefield Air Interdiction (BAI), and Air Interdiction (AI). CAS is a time critical mission, needed to help ground forces. Because we generally don't know what the ground-based threat will be it is dangerous; however survivability must not be an issue in determining if it is carried out or not. Being unmanned and highly survivable JSAAWS can carry out this mission under all circumstances and in the shortest possible time.

Concealment, camouflage, and deception (CCD) capabilities of military ground vehicles are rapidly increasing, while signature control is increasing. All of this makes it harder to find and identify mobile targets when they are stationary. There are a lot of targets in total and achieving multiple kills per sortie, rather than the current multiple sorties per kill, would be a real plus.

One option with a JSAAWS would be to only attack these targets, armor, APCs, artillery, etc., just before they get close enough to the forward line of troops (FLOT) to impact troops on the ground. Getting them while they are moving will to some extent mitigate the CCD issue. This also does away with the longer, less productive, BAI and AI missions against these type of targets and so increases efficiency. It also decreases collateral damage considerations. The targets will be far enough away from our troops so friendly fire is not a worry, but close enough to the FLOT that there will be minimal enemy collateral damage considerations because everything will soon be in the field of fire from ground forces. We could have a rolling kill line just far enough in front of the ground forces so that we minimize time to kill while not putting ground forces in jeopardy.

This has psychological consequences. If an enemy knows he can/might be killed anywhere he has no reason not to get to the FLOT to fight back. If however he knows that the likelihood of being killed from the air increases by a lot within, ten kilometers of the FLOT, he might be less inclined to hurry to get there.

Armed Recce and ASuW in the Littoral. These two missions have many common characteristics. The environment and ROEs highly asymmetric. They are carried-out in congested environments where targets will be among many non-targets and collateral damage is a major issue. Hence there are many more restrictions on us than on an adversary. Pop-up threats will be present and we will be looking to engage relocatable and moving targets. These things require either self targeting or continuous targeting from off-board assets. A survivable JSAAWS allows a longer time within which to make shoot/no-shoot decisions. If identification is a problem JSAAWS can get closer to a potential target thus increasing the probability of proper identification and decreasing the probability of killing the wrong thing. If a no-shoot decision is made and JSAAWS is lost no pilots are lost and the consequences are not as great.

Operational Maneuver ...from the Sea. The US Marines are developing several tactics in this area involving distributed combat cells. One example involves landing several small forces, separated in distance, who can mass fire on a given target from diverse locations rather than massing manpower and allowing easier detection and coordinated response by our enemies.

These forces will need to be able to call fire when and where it is needed. One possible solution is for several JSAAWS to loiter close at hand over enemy soil, to act as organic assets for each fire team. This would allow for precise time-on-target and rapid response without exposing pilots to extended missions in high-threat environments.

Counter Cruise Missiles. To defend against these missiles in flight is a difficult mission. If the attack is by missiles launched from dispersed sites and targeted at either dispersed sites or a single site there are a number of functions that must be accomplished. The first function is to find them. This could be done by airborne or spaceborne assets. The difficulty will arise from the degree of stealth in the cruise missiles. The second function will be to intercept the cruise missiles before they reach the target. If the missiles are carrying chemical, biological or nuclear weapons then the issue becomes one of intercepting them before they cross the FLOT. Finally the missiles must be destroyed. One solution to the intercept problem is a very fast counter-cruise-missile missile, keyed by the observation platform and launched from a surface or airborne platform, and having sufficient guidance and fuzing capability to get to and destroy the cruise missile. The issue here is cost and capability. Another solution is wide area coverage provided by a few highly capable forward-deployed JSAAWS, which can both target and shoot at the missiles. This mission will require a highly capable sensor suite to provide the wide area coverage, even if cued from other assets, and either a high speed JSAAWS or a high speed, high capability weapon. A high speed JSAAWS would provide the challenge of mixing loiter and speed in a single airframe. A third solution is to provide high density coverage over a defensive belt using numerous, mediocre, but armed, JSAAWS. The belt must be wide enough to allow for second chance detections and second shots. The key will be sustainability of large numbers of loitering airborne defenders. These JSAAWS would need loiter capability and sensors that can detect ground-hugging, low observable threats. The key will be to keep the price down, while maintaining sufficient capability.

If the attack is by a large number of cruise missiles, more ordnance is necessary to destroy them. This presents payload issues for the JSAAWS, be they few and capable or many and mediocre. No matter how many JSAAWS there are there will be more cruise missiles and some JSAAWS will be called upon to deliver multiple kills. If this is done with close-in weapons such as guns and rockets then the JSAAWS must make each kill quickly and then move on the catch the next cruise missile. This will require a JSAAWS with high speed. If longer range weapons are used the JSAAWS will need to carry enough of them to kill a sufficient number of the cruise missiles.

Offensive Counter Air. This is a time critical mission. Attack of highly defended airfields with readily identifiable targets, such as runways and revetted aircraft, is well suited to a JSAAWS. Aircraft are easier to find and kill on the ground. They don't maneuver or shoot back with highly capable air-to-air missiles, although airfield air defenses do shoot back, and they are cheaper to kill on the ground using things like guns, rockets, dumb bombs, or even JDAMs, vice AMRAAM or AIM-9 in the air. The use of guns and rockets would also increase the number of kills per sortie because of the ability of the JSAAWS to carry more bullets or rockets than bombs.

Defensive Counter Air. A highly maneuverable JSAAWS would overcome the exchange ratio problem. Such a system could either survive most missile attacks or defeat threat aircraft in the merge/post-merge battlespace by out-maneuvering them and destroying them before they launch their close-in missiles. Also the psychological consequences on an enemy if he knew he was facing an uninhabited system rather than another pilot could be extremely demoralizing.

Some arguments on exchange ratio make the case that we won't have to worry about fighting superior aircraft and weapons because no adversary can afford many of them. They are bought not to fight NATO but to intimidate, and be used against, regional rivals and they won't be risked against us because we have superior pilots and vastly

superior numbers. However, even if we do end up fighting superior aircraft and weapons we will eventually defeat them, and if it takes the loss of some of our aircraft that will not impact the campaign because of our overwhelming number advantage.

This argument breaks down if zero casualties becomes an explicit, or implicit, requirement as it might in less than MRC level conflicts. Witness the Scott O'Grady affair in Bosnia where we risked the lives of many more personnel and the loss of much more equipment to try to prevent his capture. It also breaks down in scenarios where the Navy is the first or the only service on the scene. Under those circumstances we have very few aircraft on scene and can't afford to lose any. It also breaks down in enforcing no-fly zones when we might see exclusively few on few engagements. These engagements will all be at the adversary's initiation and could put us either at parity or at a numerical disadvantage at the time of the fight. This coupled with superior weapons in an adversary's hands could make enforcing a no-fly zone either impossible or extremely expensive as we increase the number of platforms on patrol.

JSAAWS also helps overcome some IFFN issues. Currently survival in air-to-air engagements is largely a matter of killing your opponent before he shoots at you. This means getting the first shot off at fairly long ranges, which can be in conflict with ROEs that say we need positive, visual, identification. With a JSAAWS that is survivable by means other than killing the opponent, for example superior maneuverability, we have the option of switching to an ROE that is - kill only when positive identification has been made - with very little danger of losing a JSAAWS.

One option would be to only fire if fired upon or to use a datalink to have a remotely located operator make the firing decision. Since there is no danger of losing a pilot, and the JSAAWS would be highly survivable, it could get a lot closer to the incoming aircraft before it had to make a decision on what actions to take.

While survivability might not be as much of a concern for the F/A-18 E/F and the F-22, both of which are postulated to be much more survivable than the air superiority fighters of the past, it will continue to be an issue for the older generation of aircraft that would still be part of the force mix if not replaced by a JSAAWS. Another potential advantage of using JSAAWS is that if the only manned fighters in the air are the adversary's, we could exercise the option of risking a beyond visual range shot with only reasonable indication (>95%) that the aircraft is an enemy; whereas if we had manned aircraft in the area, the requirement would be >99.999% positive visual identification.

6 FUNCTIONAL CONCEPTS

Three concepts have been defined that cover all of the missions for a Naval Expeditionary Force. They are also from diverse parts of the potential design space.

The high-end concept is the Highly Maneuverable Lethal Vehicle presented in detail in paper 4 of this Conference.

It relies on capabilities superior to the threat in almost all areas to achieve lethality and survivability. Cost savings are obtained through decreased O&S and improved effectiveness.

This would be a multi-role system for most air-to-air and air-to-surface missions. It is very capable, but could costs as much as, or more than, a manned aircraft. This system has an extensive sensor suite for both targeting and survivability. Data link requirements are limited because the system is highly intelligent, and highly autonomous. It is highly maneuverable and requires some countermeasures. It uses short range, light, inexpensive weapons. Our view is that extensive technology development is needed in some critical areas before system-level demonstrations are viable.

The air arsenal ship is a concept that has been put forward by the US Air Force. It would have limited air-to-air and air-to-surface roles. Potential missions include Strategic Strike, OCA, Littoral ASuW, Armed Recce, Counter TBM and Cruise missiles. It requires a long range sensor suite for targeting and would have extensive datalink requirements because it would serve in a surveillance and reconnaissance role as well as a lethal role. It would be moderately intelligent and moderately autonomous. It relies on very high altitude and very low observability for survivability. It would employ current and advanced long range weapons. To take full advantage of its very long time on station it will need a large loadout of weapons. Cost savings are obtained via decreased O&S. Extensive technology maturation is needed in several areas before system-level integration demonstrations would be feasible.

The low-end concept would have capability in a limited, but operationally significant, set of air-to-surface missions, CAS, BAI, AI, SEAD, Indirect Fires. However included in this mission set are a significant number of the total targets. It achieves survivability by aggressive nap-of-the-earth flight, requiring a terrain and obstacle avoidance system. It could have a missionized sensor suite. Targeting will all be at short range requiring either a minimal on-board sensor suite or potentially the use of off-board targeting and GPS only on-board. It would have moderate datalink requirements because most communication would either be short range or via relay

systems, and the data presented will be limited imagery of the proposed targets. Because of the limited mission set the system will only be moderately intelligent and have limited autonomy. It will utilize existing inexpensive weapons, such as guns, rockets, and dumb bombs in a direct attack mode wherever possible. STOL capability is inherent in the concept which would make for easier carrier integration or use on small deck ships Integration demonstrations, not technology development, is needed to help mature this concept. Cost savings are obtained via a lower unit cost, decreased

O&S, and use of existing, inexpensive ordnance. One other attractive implementation could be a V(S)TOL version. This would allow use by the Marines at minimal on shore facilities. It would also make carrier integration easier by using less deck space, for example helo pads. It would also allow the use of any air capable ship as a launch platform. The low end concept, whatever its implementation, is the preferred concept for initial introduction of a JSAAWS since it requires the least RDT&E, is the lowest cost, and still takes on some of the most important air-to-surface missions.

7 CONCLUSIONS

JSAAWS is a new aviation concept. As such it is a highly complex system that is part of a much larger, and hence even more complex system of systems. There are similarities to aircraft, UAVs, and weapons, but there are also fundamental differences that must be understood before we will have an optimized system. Such a system would provide an opportunity to "break the mold" of expensive upgrades to expensive-to-maintain aircraft nearing the end of their useful life, as well as providing a potential solution to the fundamental problem of cost of ownership. JSAAWS cannot be considered separate from investment in the rest of force structure and before we make any major investments we need to thoroughly understand their potential contribution to Naval Aviation. If JSAAWS are to be implemented we will need a deliberate and planned evolution to maximize leverage of legacy force. In order to minimize cost and maximize benefit we need to begin understanding and planning now.

UNCONSTRAINED MANEUVER AIR VEHICLE, A CONFIGURATION DEVELOPMENT

Barth W. Shenk
United States Air Force
Aeromechanics Integration Branch
Wright Lavoratory
2645 Fifth St, Ste 7
Wright-Patterson Air Force Base, Ohio 45433-7913, USA

Summary

Maneuverability-based sizing of a notional, unmanned air vehicle is presented with spin tunnel test results of a resultant configuration. Sustained load factor and roll acceleration were traded against wing loading, thrust-to-weight ratio and aspect ratio for a notional air-to-air combat mission. Prospective turn and roll performance goals were developed for an unmanned fighter, and physical limitations of thrust matching between cruise and maneuver power requirements was studied. The resulting configuration characteristics indicate that optimization of this class of vehicle requires development of inertial optimization methods and structural design methodologies for instantaneous, dynamic loads.

Nomenclature

AR	aspect ratio, b^2/S
b	wing span (ft)
BCA/M	best combination, altitude and mach number
$Cl_{\delta a}$	aileron control power (deg^{-1})
dry	no afterburning
FDGW	flight design gross weight (lb)
g	load factor, gravitational acceleration 32.174 ft/sec^2, 9.81m/sec^2
I_{xx}	roll moment of inertia (slug ft^2)
M	mach number
nm	nautical mile
$\dot{P}$	roll acceleration (deg/sec^2)
q	dynamic pressure (lb/ft^2)
S	aircraft wing reference area (ft^2)
T	thrust (lb)
TSFC	thrust specific fuel consumption (lb_{fuel}/lb_{thrust}/hour)
TO	takeoff (subscript)
T/W	aircraft thrust to weight ratio
UMAV	unconstrained maneuver air vehicle
W	weight (lb)
W/S	aircraft wing loading (lb/ft^2)

1. Introduction

In response to Air Force New World Vistas studies, Wright Laboratory initiated an effort to explore fundamental characteristics of maneuvering aircraft unconstrained with respect to human physiological limitations. This notional vehicle, according to the New World Vistas studies, ideally would be in the F-16 class, in terms of payload-range and general size. Acceleration to supersonic speed and supersonic cruise without afterburner were additional capabilities of interest.

Given the exploratory nature of the project, a sequence of investigations was performed to understand unmanned effects on configuration development. Without specific requirements, the first investigation was development of prospective goals for maneuver performance. Second, sizing studies were conducted to assess tradeoffs between physical parameters and the maneuver goals, and determine a probable planform. Third, a subscale UMAV model was statically and dynamically tested to verify planform maneuvering stability and control characteristics and validate the planform development process and tools.

The general results of the study indicate that without human physiological considerations: (1) steady-state maneuver performance levels are constrained by payload-range requirements, which are driven by aero-propulsive efficiency needs, (2) superior instantaneous maneuvers are easily achieved with basic planform and control system layouts, (3) development of structural design methods for dynamic, instantaneous load optimization are needed and (4) methods for considering inertial optimization during initial planform development should be used if the full combat potential of UMAVs is to be realized.

2. UMAV Conceptual Design Space

Paper presented at the AGARD MSP Symposium on "System Design Considerations for Unmanned Tactical Aircraft (UTA)", held in Athens, Greece, 7-9 October 1997, and published in CP-594.

2.1 Performance Design Space

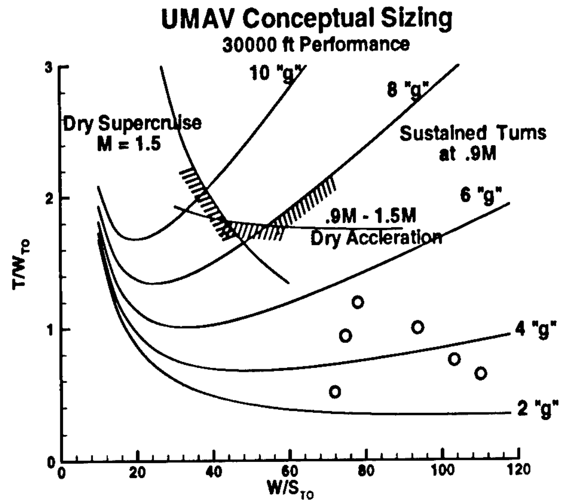


Figure 1. Performance Sizing Plot

Figure 1 illustrates the general relationship of aircraft takeoff thrust and wing loading requirements to achieve maneuver levels that may be reasonable to pursue for a light fighter configuration with superior maneuver ability.

Figure 1 was developed using the methods of Reference 2 at a benchmark altitude and speed with a FDGW of 80% W_{TO}. The thrust model is based on statistical low-bypass ratio engine cycles, and the drag polar model is based on a statistical polar shape representative of current fighter characteristics.

For maneuverability perspective, the data points on the plot (circles) represent capabilities of current, manned systems. At this design point, the combination of 8g sustained turn capability at altitude with dry supersonic acceleration to dry supersonic cruise is well beyond the capability of current systems.

Conflicting trends are evident, which bound a potential solution space. Power requirement for sustained load factor turns increases exponentially for turns in excess of 4g, with optimum wing loading approximately 20 psf (958 N/m^2). For an F-16 class vehicle weight, this would result in wing areas over 1000 ft^2 (93 m^2), which aren't feasible for a light-weight vehicle. Dry acceleration represents the critical lower boundary for power required.

2.2 Design Space Analysis

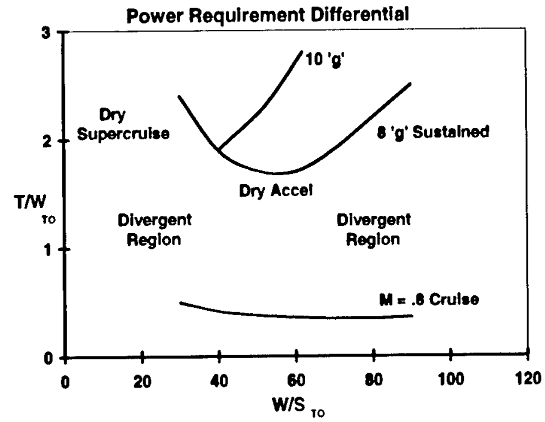


Figure 2 Power Requirement Differential

The discrepancy between power required for maneuver performance and basic subsonic cruise is illustrated in Figure 2, in which the T/W_{TO} requirement boundaries of Figure 1 have been isolated.

Maneuver power requirements are at a minimum for wing loading of 50 - 60 psf.(2394 - 2873 N/m^2), and thrust loading between 1.7 and 1.8. This region represents both the smallest allowable engine and minimum difference between maneuver and cruise power required. This difference is a rough measure of change in throttle setting. At lower and higher wing loading ranges, the power requirements between maneuver and cruise diverge. Progressively larger engines are needed, cruising on progressively lower throttle settings. Cruise efficiency decreases, resulting in successively larger vehicle sizes to accommodate required mission fuel.

In general, low bypass ratio engines do not operate efficiently at very low power settings, where specific fuel consumption increases dramatically, as shown by data in Figure 3, reproduced from Reference 3. At successively lower throttle settings, the total fuel burn for cruise actually becomes greater even though thrust is low, given that the majority of mission time is spent at the cruise flight condition.

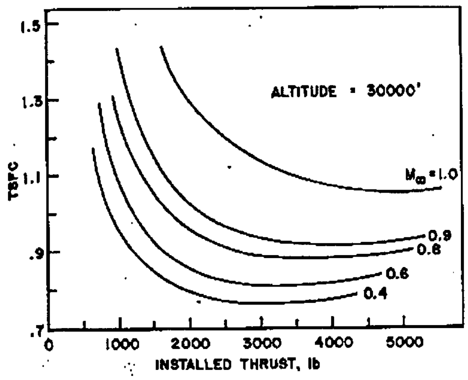


Figure 3 Low Bypass Ratio Turbofan Data

This aero-propulsive divergence effect was verified in the sizing analyses. Figure 4, generated in the sizing studies, depicts the effect of poor thrust matching on overall UMAV vehicle size. Even the highest T/W values fail to achieve performance goals without compatible wing loading combinations.

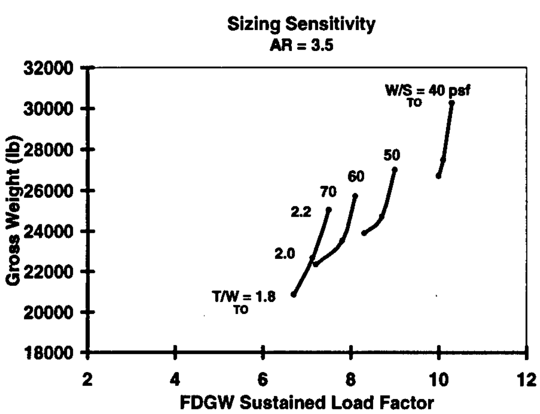


Figure 4 Aero-Propulsive Matching

3. UMAV Combat Requirements

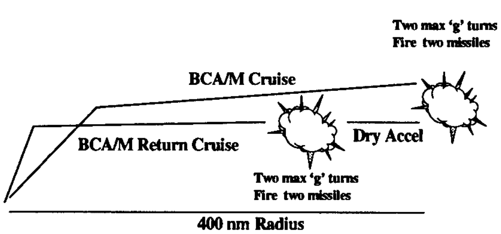


Figure 5 UMAV Mission Profile

The mission in Figure 5 represents a generic concept of a tactically useful range and payload combination for a light-weight fighter. Following a takeoff, a minimum-time climb to 30000 ft (9144 m) is followed by an optimum cruise to 400nm (740km) radius. At this point, combat is modeled as two maximum effort, 360 degree turns at constant altitude and mach number (30000 ft, M=.9). One air-to-air missile is fired at the completion of each turn.

A dry acceleration to supersonic speed is followed by transonic combat identical to the first. The remaining return range is flown at optimum cruise, followed by descent and landing with 5% mission fuel reserve. All fuel and weapons are carried internally.

Mission analysis was performed using CASP, Reference 1, an energy method-based sizing and performance program. The Pratt & Whitney F119 engine was used as a reference engine cycle for configuration mission sizing parametrics.

4. UMAV Roll Performance

Combat maneuverability requires superior rolling performance as well as turn performance. Steady-state roll rate is a common figure of merit for roll performance. However, steady-state conditions are generally not commonplace in combat. Roll acceleration was used as a target design quantity to denote the aircraft sensitivity response to a control input. The design goal for UMAV roll acceleration was a 50% increase in magnitude compared to current, light-weight fighters at the maneuver design point.

As determined in Figure 1, increasing sustained turn load factor requirements tend to drive configurations to successively larger wing areas to reduce induced drag. Successively higher aspect ratio may compliment this effect to an extent, and also improves the subsonic cruise performance of the vehicle. Roll performance, however, generally degrades as aspect ratio increases through the cumulative effects of structural weight increase, rolling moment of inertia growth as wing mass moves outboard and aeroelastic effects induced by wing and controls interactions.

4.1 Roll Acceleration Approximation

For configurations featuring mid-fuselage mounted wings, no dihedral angle and at negligible angles of sideslip, roll acceleration may be expressed using:

$$(1) \quad \dot{P} = (q * S * b / I_{xx}) * Cl_{\delta a}$$

from Reference 5, roll inertia may approximated from Reference 6:

$$(2) \quad I_{xx} = (b^2 * W * R^2_x) / (4 * g),$$

in which R_x is a non-dimensional radius of gyration which may be approximated by a statistical average of data for aircraft of a similar type. Reference 6 contains data tables listing values of non-dimensional radii of gyration for a large number of aircraft, grouped according to type. For this study, $R_x = 0.235$ was used, being an average of six similar fighters between 16,000 and 37,000 pounds gross weight (71171 - 164583 N). Based on lambda wing planform test data, $Cl_{\delta a} = -.002$/deg was used as a representative value for aileron control power at the maneuver point condition.

Equations (1) and (2) can be combined to create an approximate expression for roll acceleration in terms of aspect ratio and span loading:

$$(3) \quad \dot{P} = -1164 / (AR * (W/b))$$
$$\text{SI units} = -118.7 / (AR * (W/b))$$

This expression, to a first order estimate, accounts for small changes in vehicle geometry and weight on roll inertia and acceleration, respectively. Accuracy is restricted by physical similarities with database aircraft, including weight, geometry and control surface layout.

Roll acceleration was calculated using (3) for CASP sizing results at a given wing loading, thrust loading and aspect ratio combination.

5. Trade Study Configuration

Figures 5 and 6 present the general arrangement of the trade study configuration used. For sizing studies, wing planform, fuselage and tail geometry were held constant. Wing area, aspect ratio and longitudinal position were varied.

The wing planform used is a generic "lambda" planform, so named for its resemblance to the greek letter λ. This type of shape is convenient for aspect ratio and sizing manipulations, as well as volumetrically effective for internal storage of fuel, weapons or landing gear. Planform test data from Reference 7 was used in the studies.

5.1 Static Margin Considerations

Optimum static margin for each value of aspect ratio and wing loading was found by varying

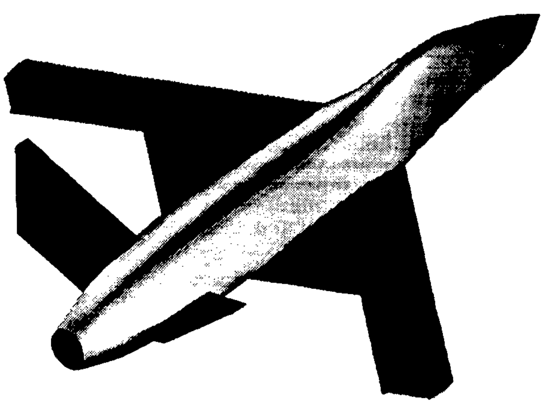


Figure 6 UMAV Orthogonal

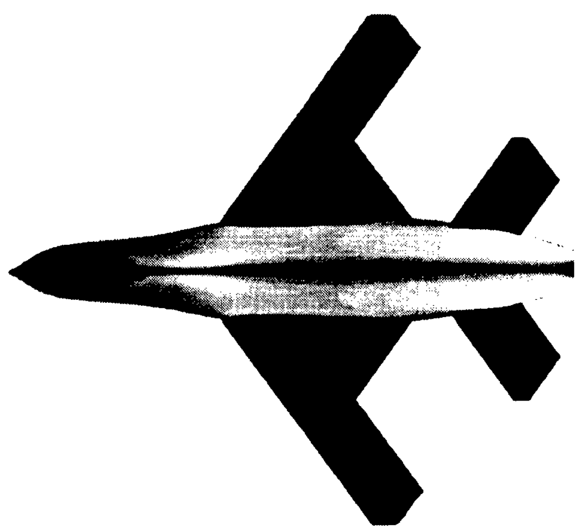


Figure 7 UMAV Plan View

wing longitudinal position in the sizing process to achieve maximum sustained load factor at the maneuver design point.

Statically unstable configurations tend to be capable of higher load factors than stable planforms due to the net reduction in wing loading created by the positive lift of the horizontal tail required for trim. This positive lift increment decreases wing lift required for a given load factor, reducing the induced drag and pitching moment generated by the wing. This effect is only realized to the point at which induced trim drag from the tail becomes significant. Optimum static margin for turn performance varied from 4% to 14% unstable for the configurations studied.

6. Trade Study Results

6.1 Results for Thrust Loading = 1.8

6.1.1 Maneuver Trade Study

Figures 8 and 9 show the general trends of sustained load factor and roll acceleration with aspect ratio and wing loading.

The analysis yields no common aspect ratio and wing loading combination which achieves both the sustained turn rate and roll acceleration goal simultaneously. The closest match occurs at a wing loading of 50psf (2394 N/m^2), where an aspect ratio of 3.5 or greater is necessary to achieve load factor and an aspect ratio of 3.2 or lower is required to meet roll acceleration objectives.

Generally, lower wing loading produced more favorable maneuver characteristics.

6.1.2 Gross Weight Sensitivity

In Figure 10, UMAV gross weight for the overall mission generally decreases with increased aspect ratio in this study range.

This relationship is very sensitive for the wing loading of 50 case, while being much more stable at a wing loading of 60. This stability indicates a good wing loading match for cruise requirements, but is not compatible with the maneuver trades discussed above.

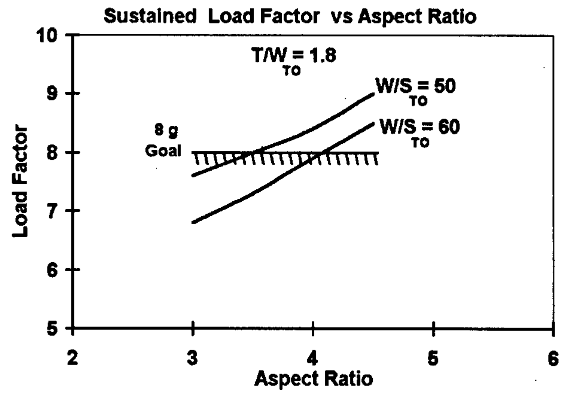


Figure 8. Sustained Load Factor Trends

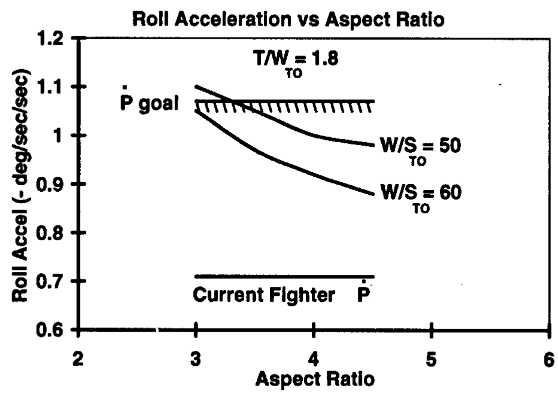


Figure 9. Roll Acceleration Trends

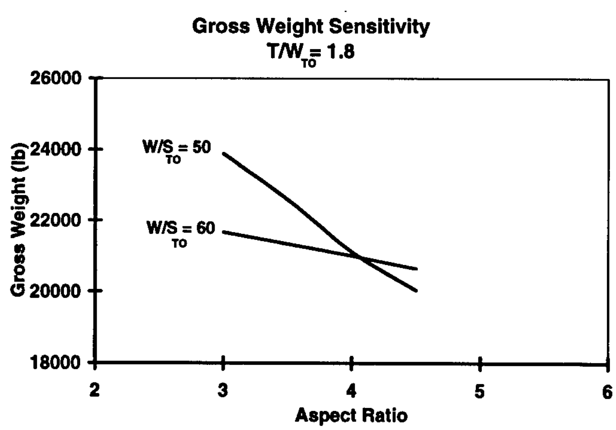


Figure 10. Gross Weight Sensitivity

6.2 Results for Thrust Loading = 1.7

6.2.1 Maneuver Trade Study

Aspect ratio sensitivities shown in Figures 11 and 12 show that turn and roll performance goals are not attainable for the higher wing loading case. At a wing loading of 50, however, there are compatible aspect ratio solutions for both performance goals.

6.2.2 Gross Weight Sensitivity

Gross weight trends in Figure 13 indicate that this lower thrust loading is a more stable match in terms of overall mission sizing. An increase in gross weight near AR=3.5 is associated with increased fuel burn due to higher induced drag and throttle setting in combat segments of the mission. Further increase in aspect ratio alleviates this effect with increased cruise efficiency.

6.3 Combined Solution Space

Figure 14 indicates a solution space in which both maneuver requirements may be achieved. This solution occurs with a thrust loading of 1.7, wing loading of 50psf, (2394 n/m^2) and aspect ratio of 3.6. This combination of parameters yields a mission gross weight of approximately 21300 lb, (94745N).

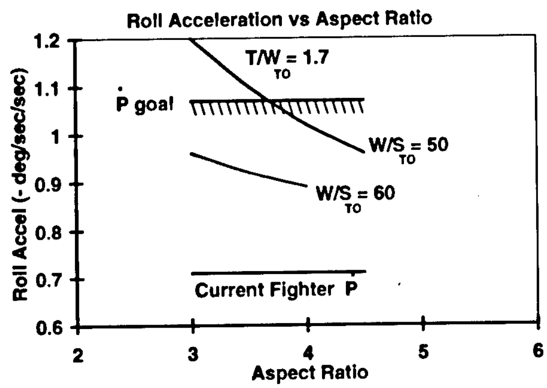


Figure 12. Roll Acceleration Trends

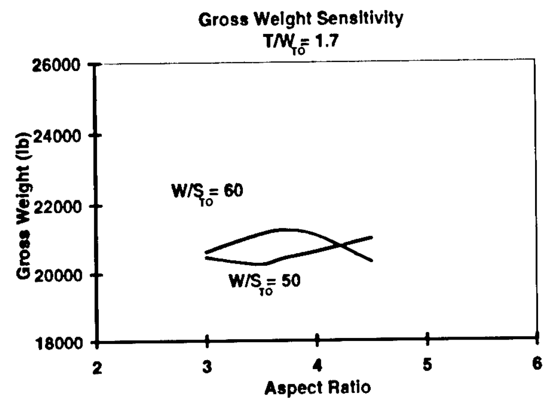


Figure 13. Gross Weight Sensitivity

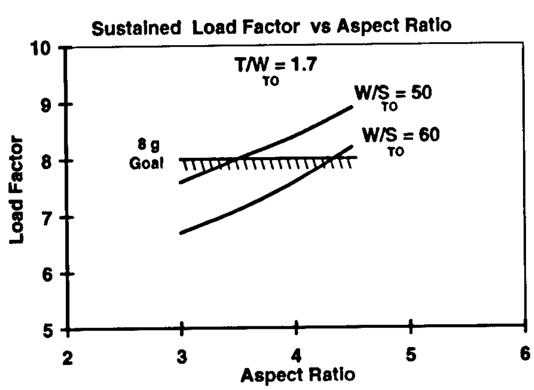


Figure 11 Load Factor Trends

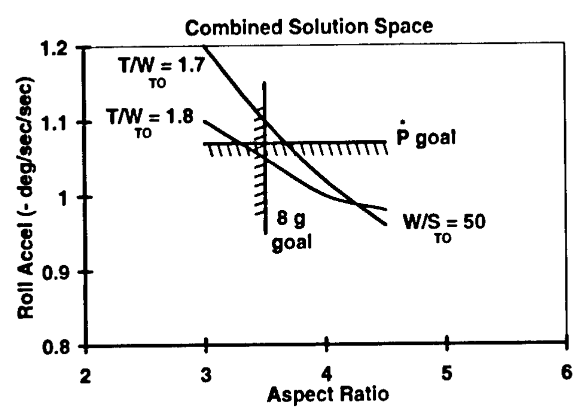


Figure 14. Combined Solution Space

6.4 UMAV Baseline Configuration

The baseline UMAV is shown in Figure 12 with physical properties determined from the sizing analysis. Table 1 lists UMAV basic mass properties as compared to a historic average of manned, internal-carriage, supersonic fighters. A nominal percentage of empty weight for pilot and cockpit furnishings was deducted in the sizing process.

The sizing results are best-case, since unmanned operation was modeled as only an empty weight loss, with no additional weight to simulate a more complex avionics suite. The higher empty weight and lower fuel fraction reflect the dominance of propulsion system weight on vehicle mass.

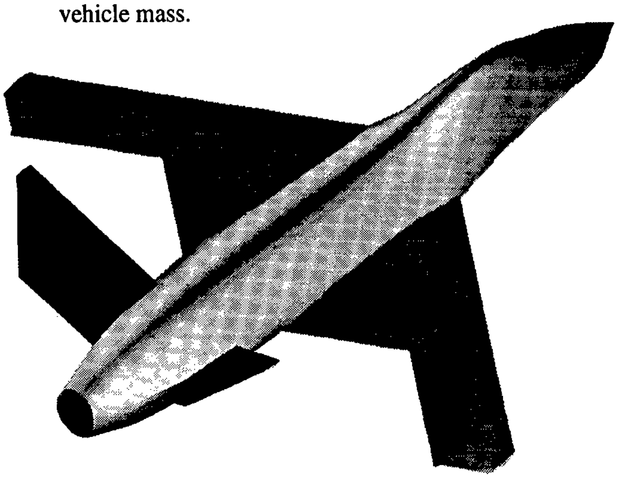


Figure 15 UMAV Baseline

7. Wind Tunnel Testing

Wind tunnel testing of a 1/9 scale model UMAV configuration shown in Figure 13 was conducted in cooperation with Birhle Applied Research at the Large-Angle Multi-Purpose (LAMP) vertical wind tunnel and testing apparatus facility in Germany.

Tests were performed prior to completion of the sizing study. Model design and fabrication was done for an interim UMAV configuration.

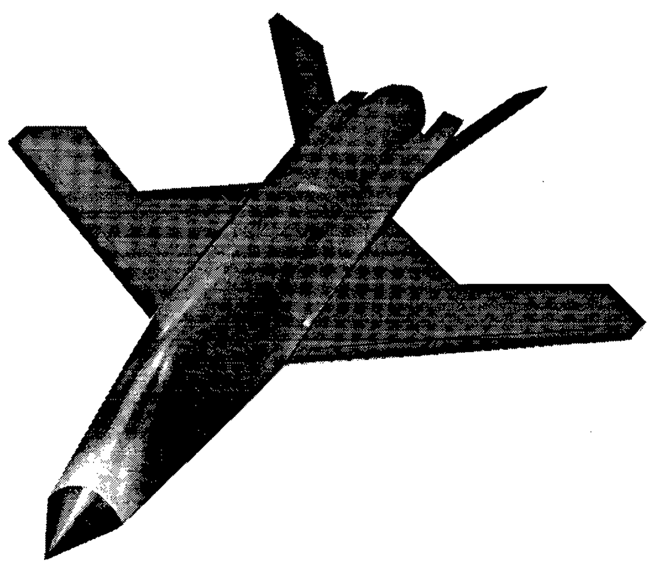
Table 1 Mass Properties Comparison

	W_{empty}/W_{TO}	$W_{payload}/W_{TO}$	W_{fuel}/W_{TO}
UMAV	0.66	0.07	0.27
Mean	**0.61**	**0.08**	**0.31**

Table 2 **UMAV Geometric Characteristics**

AR = 3.6	**Leading Edge Sweep = 40 deg**
T/W_{TO} = 1.7	**Tail Volume Coefficient = 0.25**
W_{TO} = 21300 lb = 94745 N	**Mean Aerodynamic Chord = 14 ft = 4.27m**
Length = 45 ft = 13.7m	**Tail Cant Angle = 45 deg**

Figure 16 UMAV Wind Tunnel Model



7.1 Test Description

UMAV stability and control characteristics were studied using a rotary balance. Rotary aerodynamic data are obtained in two steps. First, the inertial forces and moments (tares) acting on the model at different attitudes and rotational speeds must be determined. Ideally, these inertial terms would be obtained by rotating the model in a vacuum, thus eliminating all aerodynamic forces and moments. As a practical approach, this is approximated by enclosing the model in a spherical structure which rotates the model without touching it, such that air immediately surrounding the model is rotated with it. As the rig is rotated at the desired attitude and rate, the inertial forces and moments are measured and stored on magnetic tape for later use.

The enclosure is then removed and the force and moment data recorded with the wind tunnel operating. The tares, measured earlier, are then subtracted from these data, leaving only the forces and moments, which are converted to coefficient form. Historical background for this type of testing is discussed in Reference 3.

The UMAV low speed stability characteristics include all nonlinear dependencies on angle of attack , sideslip, wind axis rotation and body axis rotation. UMAV control characteristics include the same nonlinear dependencies with control interaction effects. To simulate maneuver point conditions, computational mach increments to the magnitudes of pitching moment, normal force and axial force were applied. General trends for nonlinear dependencies and interaction effects were assumed to be the same.

7.2 Model Description

The UMAV model shown in Figure 15 was derived at an interim point in the sizing study. It represents a wing loading of 60psf (2873 N/m^2), thrust loading of 1.8, and 3.6 aspect ratio. For control surfaces, the 1/9 scale model incorporated 20% chord leading edge flaps and 30% chord trailing edge flaps and ailerons, based on constant-chord section chord length. The canted tails were all-moving, outboard of the fuselage.

Figure 16, a reproduction of the sizing study trend, indicates a predicted load factor of approximately 7.2 for this configuration.

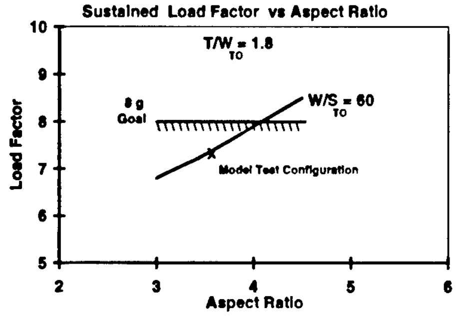


Figure 16 Predicted Model Performance

7.3 Test Results

Data gathered from the test was used in a flight simulator program developed by Birhle. A roll comparison between the UMAV configuration (lambda) and a light, manned fighter (F-X) was conducted at maneuver design point conditions.

For approximately equal values of aileron control power, $Cl_{\delta a}$, and aileron deflection, the time histories of roll acceleration and roll rate responses are shown in Figures 17 and 18, respectively. Both trends compare limited control response consistent with acceptable handling qualities to unlimited responses.

In either case, maximum roll responses for either vehicle are attained when handling quality response limits are removed from the flight control system. UMAV responses are orders of magnitude greater than the current capability, and, in general, target values for roll acceleration in the configuration development process were achieved with a fairly simple methodology.

Assuming that some artificial, autonomous system for situational awareness and decision-making is present and able to process and manipulate sensor information at rates faster than the rates and accelerations of the vehicle's response to control deflections, these levels of control sensitivity represent a new potential in combat agility, in which combat maneuvering and handling qualities are defined by the capabilities of the flight control system.

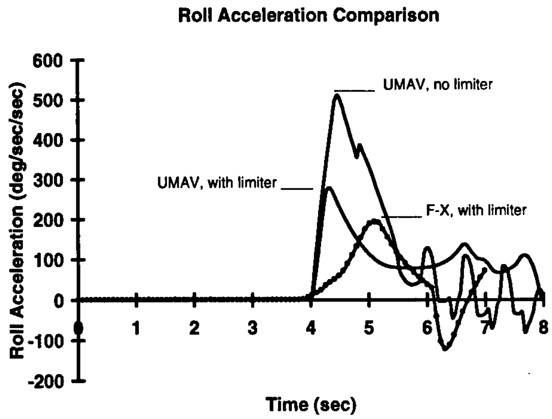


Figure 17 UMAV Roll Acceleration

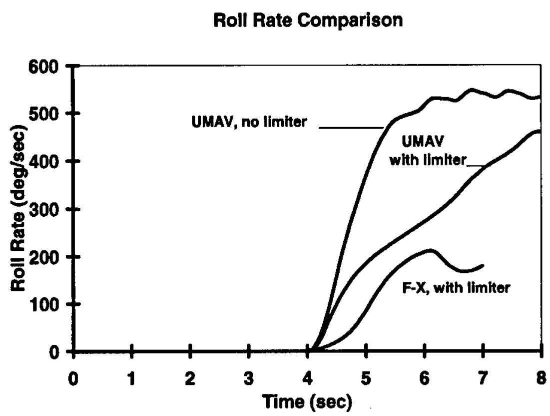


Figure 18 UMAV Roll Rate

8. UMAV Off-Design Performance

Although steady-state, sustained load factor was limited by payload-range in this study, instantaneous "g" load factor is not, since it is not a steady state condition requiring thrust equal to drag. As a result, much higher instantaneous load factors could be exploited by a UMAV, pending only structural design limits. Figure 19 illustrates the UMAV design is aerodynamically capable of instantaneous 'g's more than double the sustained 'g's at a given altitude and mach number, based on empirical estimates for maximum trimmed lift coefficient shown in Figure 20.

Structural limitations would determine usable levels of maneuver load factors. However, traditional structural design and weight estimating methods are based on sustained loads. Methods developed to design for instantaneous loads would be required to accurately optimize the design of a UMAV. For the trade study, an ultimate load factor of 14 at FDGW was used with conventional weight estimation methods.

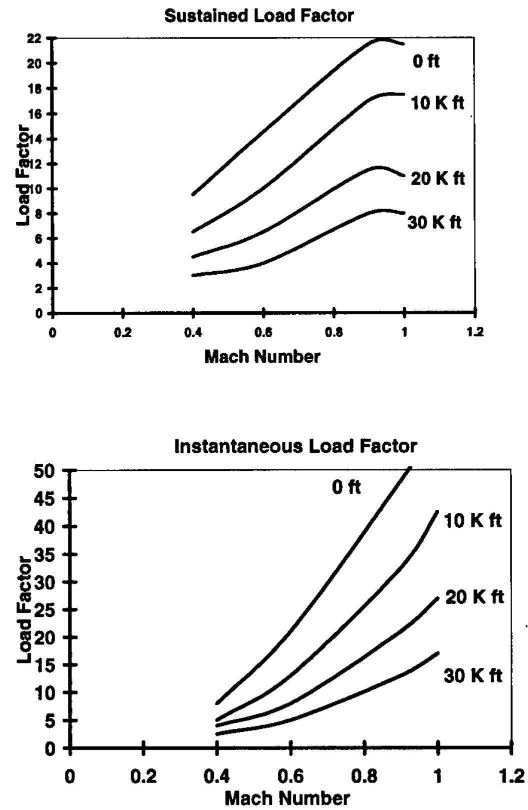


Figure 19 UMAV Maximum Load Factors

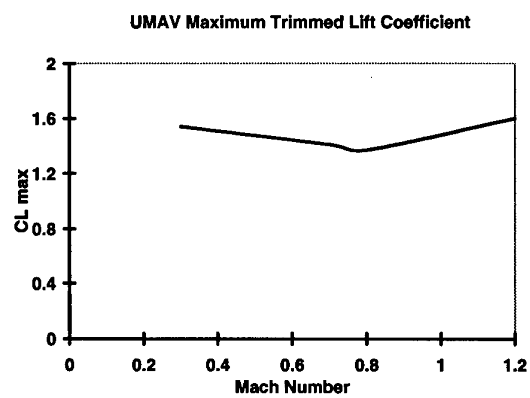


Figure 20 UMAV Maximum Trimmed Lift

9. Observations

Development of UMAV configurations to exploit combat maneuver capability may be easily incorporated early in the design process. Optimization of UMAV configurations, however, will require the development of non-traditional methodologies to fully exploit their potential capabilities.

Although removing the human pilot also removes physiological limitations on aircraft maneuver, design for useful range with payload constrains steady-state maneuverability to levels of thrust loading and wing loading where aero-propulsive efficiency is possible in the cruise mode. Steady state maneuver levels may be well in excess of current manned fighter capability, but not by orders of magnitude as one may expect.

UMAVs do have magnitudes of combat maneuvering advantage in repetitive, instantaneous maneuvers. Aircraft of this type may be designed for control effectiveness and sensitivity well beyond what are considered good handling qualities, since handling quality for this class of vehicle is defined only by the limits of the flight control system. Accurate, first order planform development for target values of roll acceleration and pitch authority may be incorporated early in the configuration sizing process with simple geometric relations. This process is also free from pilot visibility restrictions, which partially constrain wing, forebody and inlet geometries in conventional planform shaping.

Sizing methodologies must also include tradeoff studies between control surface sizing for response rates and accelerations and volume, weight and data processing rate of the on-board artificial intelligence system. On-board decision making will probably be necessary. It is unlikely that a UMAV could be remotely piloted successfully in aerial combat situations, due to finite limitations on time to transmit, interpret and receive response to sensory information effectively at the extremely high levels of UMAV maneuverability.

Methods for considering inertial optimization of vehicle planform early in the configuration layout and sizing process have the potential to minimize the number and size of necessary control surfaces to achieve desired maneuver/rotation goals about any axis. To an extent, this type of methodology exists for space-based satellite design, in which inertial characteristics are tailored to suit orbit dynamics and vehicle functions. Analogous methods may potentially be developed for aircraft applications.

Structural design and weight estimation methods developed for dynamic, instantaneous loading will be needed for physically accurate UMAV mass property analysis.

These methods, combined with traditional aero-propulsive analysis methods will be required to optimize and develop UMAVs, with their unique performance capabilities, as a distinct class of combat aircraft.

References

1. USAF Scientific Advisory Board, "New World Vistas: Air and Space Power for the 21st Century" 1996.

2. Mattingly, J.D., Heiser, W. H. and Daley, D.H, Aircraft Engine Design, American Institute of Aeronautics and Astronautics, Inc., 1987.

3. Nicolai, L. M., Fundamentals of Aircraft Design, METS, Inc. 1984.

4. "Combat Aircraft Synthesis Program, CASP", computer program.

5. Mc Donnell Douglas Aerospace Company, "Tailless Fighter Aerodynamic Assessment", Task Order Contract F33615-94-C-3000, unpublished report.

6. Roskam, J., Airplane Design, PartV, Component Weight Estimation, Roskam Aviation and Engineering Corporation, 1985.

7. Adamczak, D.W., "Experimental Investigation of a Lambda Wing Configuration at Subsonic Speeds", WL-TR-96-3148, December, 1996.

Sensor Alternatives for Future Unmanned Tactical Aircraft

E. L. Fleeman
The Boeing Company
3370 Miraloma Avenue
Anaheim, CA 92803 U.S.A.

SUMMARY
This paper addresses the enabling technologies of the sensor suite for the next generation Unmanned Tactical Aircraft (UTA). An assessment is made of target sensors, communication sensors, and navigation sensors that are used in the UTA intelligence, surveillance, reconnaissance, communication, and target designation missions. Emphasis is given to the classes of UTAs that operate at stand-off altitudes and ranges outside the effectiveness envelope of typical threat air defenses and jammers.

Primary environmental factors that are addressed in the paper are world-wide cloud cover and rain rate. The effects of cloud cover and rain rate on sensor performance are evaluated for synthetic aperture radar (SAR), passive millimeter wave (mmW), and electro-optical (EO) sensors. The synergy of radar frequency (RF) sensors to improve the sensor suite performance in cloud cover and rain rate is addressed.

The paper also addresses the enabling technologies that are required for real time, low false alarm rate (FAR), automatic target recognition (ATR) and precision targeting. A target sensor suite is postulated that is based on multi-spectral, multi-dimension discriminants of the target. An X-band or Ku-band SAR is considered to be the best overall target sensor for UTA applications. A priority ranking of other target sensors is ultra wide band (UWB) low frequency SAR, forward looking infrared (FLIR), laser infrared detection and ranging (LIDAR), visible, and passive mmW. The Year 2007 sensor suite would cover the multi-spectral range of VHF frequency to visible wavelength and the multi-dimensional parameters of contrast, two-dimensional shape, three-dimensional shape, temporal, and polarization signatures of the target.

LIST OF ACRONYMS AND SYMBOLS

	Definition
A/J	Anti-Jam
ADTS	Advanced Detection Technology Sensor
ATR	Automatic Target Recognition
C-band	3.6 GHz to 7.0 GHz
C/A	Course Acquisition
CALCM	Conventional Air Launched Cruise Missile
CARABAS	Coherent All Radio Band Sensing
CCD	Charge Coupled Device
CCM	Counter-Countermeasure
CdZnTe	Cadmium Zinc Telluride
CLO	Counter Low Observable
D	Diameter
dB	Decibel
DQI	Digital Quartz IMU
ERIM	Environmental Research Institute of Michigan
FAR	False Alarm Rate
FM	Frequency Modulation
FMCW	Frequency Modulation Continuous Wavelength
FOG	Fiber Optic Gyro
FOV	Field of View
FPA	Focal Plane Array
GPS	Global Positioning System
HgCdTe	Mercury Cadmium Telluride
Hz	Hertz (cycles per second)
ID	Identification
IFOV	Instantaneous Field-of-View (field-of-view of one resolution cell)
IIR	Imaging Infrared
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
InSb	Indium Antinimide
IR	Infrared
ITCZ	Inter Tropical Convergence Zone
Ka-band	~35 GHz
Ku-band	~17 GHz
LADAR	Laser Detection and Ranging
LIDAR	Laser Infrared Detection and Ranging
LO	Low Observable
LWIR	Long Wave Infrared
MBE	Molecular Beam Epitaxy
mmW	Millimeter Wave
MWIR	Medium Wave Infrared
PACE	Producible Alternative to Cadmium Telluride for Epitaxy
PFM	Pulse Frequency Modulation
P(Y)	Military Code for GPS Receivers
POGO	Precision On-Board GPS Optimization
PtSi	Platinum Silicide
QWIP	Quantum Well Infrared Photodetector
R	Range to Target
RCS	Radar Cross Section
RF	Radar Frequency or Radio Frequency
RLG	Ring Laser Gyro
RSS	Root Sum of the Squares

Paper presented at the AGARD MSP Symposium on "System Design Considerations for Unmanned Tactical Aircraft (UTA)", held in Athens, Greece, 7-9 October 1997, and published in CP-594.

SAR Synthetic Aperture Radar
SATCOM Satellite Communication
SHF-band Super High Frequency Band
SIGINT Signal Intelligence
SOTA State-of-the-Art
SWIR Short Wave Infrared
TBD To Be Determined
TESAR Tactical Endurance Synthetic Aperture Radar
TLE Target Location Error
TV Television
UHF-band Ultra High Frequency Band
URE User Range Error
UTA Unmanned Tactical Aircraft
UV Ultraviolet
VHF-band Very High Frequency Band
W Weight
WAGE Wide Area Guidance Enhancement
W-band ~94 GHz
X-band ~10 GHz
~ Is similar to
μ Micron (10^{-6} meter)

1. INTRODUCTION/OPERATIONAL TRENDS OF THE YEAR 2007

Until recently, most Unmanned Tactical Aircraft (UTA) used a relatively unsophisticated sensor suite that typically consisted of a FLIR sensor, a television (TV) camera, and a data link. However, the more recent UTAs, such as Predator, are beginning to carry sophisticated sensor payloads, including multiple infrared (IR) sensors and SAR sensors, that broaden the range of missions and mission performance. Improvements in UTA sensor capability are expected to continue into the next generation multi-mission UTAs. Drivers for the next generation UTAs, that will require improved sensor capability, include a broad range of missions, enhanced survivability, wide area/continuous coverage of the target area, real time ATR, low False Alarm Rate (FAR), and real time precision targeting.

Table 1 shows a typical capability of current UTAs compared to a projected typical capability of the year 2007. The General Atomics Predator UTA was selected as an example of recently introduced UTAs. Other UTAs such as Pioneer and Hunter are less sophisticated than Predator, while developmental UTAs such as Global Hawk and Dark Star will be more sophisticated than Predator. The sensor payload of Predator includes an EO sensor suite, a Ku-band SAR sensor, Ku-band and UHF-band satellite communication (SATCOM), a C-band line-of-sight data link, and a Global Positioning System (GPS)/ Inertial Navigation System (INS) navigator.

Table 1. UTA Capability Forecast

	1997 Example (Predator)	2007 Example
Typical UTA Capability		**UTA Concept TBD**
• Mission	• Surveillance, Recce, Comm.	• Add Intel, target designation, comm. relay
• Maximum Flight Altitude	• 8 km	• > 8 km
• Maximum Sensor Slant Range	• 11 km	• > 20 km
• Maximum Flight Duration	• > 24 hours	• > 24 hours
• Maximum Velocity	• 60 m/s	• 300 m/s
• Observables	• Low	• Lower
• Sensor Payload Weight	• 200 kg	• 200 kg
• ATR Latency	• Post-flight Analysis	• Real-time ATR
• ATR FAR	• High (~ 20/km^2)	• Low (<<1/km^2)
• Targeting Accuracy	• 30 m	• 3 m

Next generation sensors will provide real-time ATR and precision targeting

The Predator's EO sensor suite is the Versatron Skyball SA-144/18 Quartet sensor. It consists of a PtSi 512 x 512 MWIR FLIR, a color TV camera with a 10X zoom, a color TV 900 mm camera, and an eyesafe pulsed erbium: glass laser range finder. The diameter of the EO sensor turret is relatively small--35 cm. The turret has precision pointing with a line-of-sight stabilization accuracy of 10 μrad.

The Predator's SAR sensor is the Northrop Grumman (Westinghouse) Tactical Endurance Synthetic Aperture Radar (TESAR). TESAR provides continuous, near real time strip-map transmitted imagery over an 800 meter swath at slant ranges up to 11 km. Maximum data rate is 500,000 pixels per second. The target resolution is 0.3 meters. TESAR weight and power are 80 kg and 1200 watts respectively.

Also shown in Table 1 is a projected capability for a hypothetical UTA introduced in the year 2007. It is anticipated to have a broad range of missions including surveillance, reconnaissance, communication, intelligence gathering of threat electronic emissions, target designation for weapons attacking moving targets, and communication relay. The system flight performance is expected to be greater than present UTAs, with higher velocity, providing a larger area of coverage and faster response in getting to the target area. The current emphasis on reduced observables is expected to continue, with future UTAs having lower observables.

Advancements in sensor capability are expected to include real time ATR, orders of magnitude reduction in FAR, and an order of magnitude improvement in targeting accuracy. The advanced sensors will leverage the current advanced development (category 6.3A funding) activities that are presently under way.

2. ADVERSE WEATHER CONSIDERATIONS IN SENSOR PAYLOAD

Weather is a driving consideration in the selection of a sensor payload suite. Although a UTA usually operates at high altitude above the weather, the sensor suite must be able to see ground targets through adverse weather.

Cloud cover is a particular concern for UTA sensors because clouds are pervasive in the world-wide weather. The global average annual cloud cover is about 61 percent, with an average cloud cover over land of about 52 percent and an average cloud cover over the oceans of about 65 percent. The average annual cloud cover shown in Figure 1 is based on weather observers around the world. It is a composite of averages that vary widely with geographical location, season, and time of day.

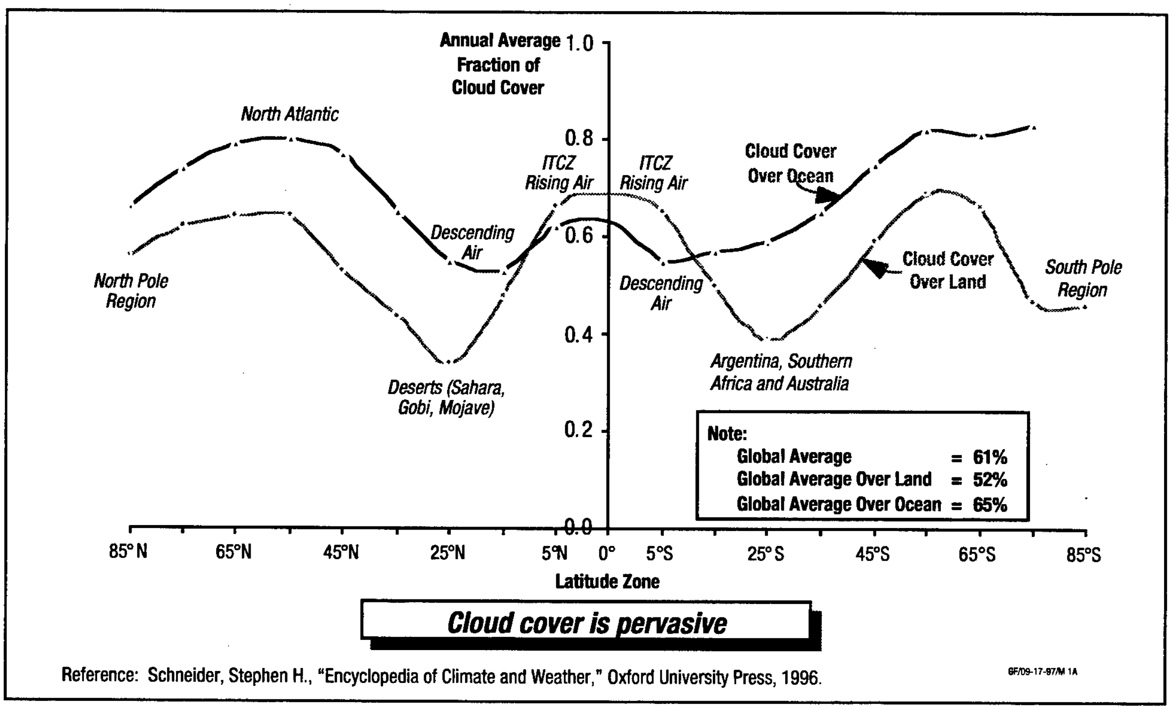


Figure 1. Cloud Cover Climatology

An example of a geographical cloud system that changes regularly with the season and the time of day is the low-level, layered stratus clouds that cover much of the world's oceans. Stratus clouds are more frequent during the summer months of the Eastern Pacific and the Eastern Atlantic and in the hours before sunrise.

Another example of a geographical cloud system that changes regularly with the season and the time of day is cumulonimbus. Cumulonimbus are large columnar clouds that can extend to high altitude. These clouds are concentrated where surface temperatures are high and there is a general upward movement of the air. An example is a zone known as the Intertropical Convergence Zone (ITCZ). In the ITCZ, the trade winds of the Northern Hemisphere converge with those of the Southern Hemisphere. Cumulonimbus have high concentrations of droplets and ice crystals, which can grow to a large size. Cumulonimbus are often responsible for the frequent summer afternoon rainfall of South East Asia, North America, and Europe, and the December, January, and February rainfall of the Amazon basin.

Rain rate is another consideration in sensor selection. Figure 2 shows the world-wide average annual precipitation (rain and snow equivalent rain) characterized as wet (greater than 1500 mm/yr), temperate (between 250 mm/yr and 1500 mm/yr), and arid (less than 250 mm/yr). It is noted that over 90 percent of the world receives less than 1500 mm/yr rainfall. It is also noted that cloud cover variations due to geography, season, and time of day are reflected in the rainfall variations with geography, season, and time of day.

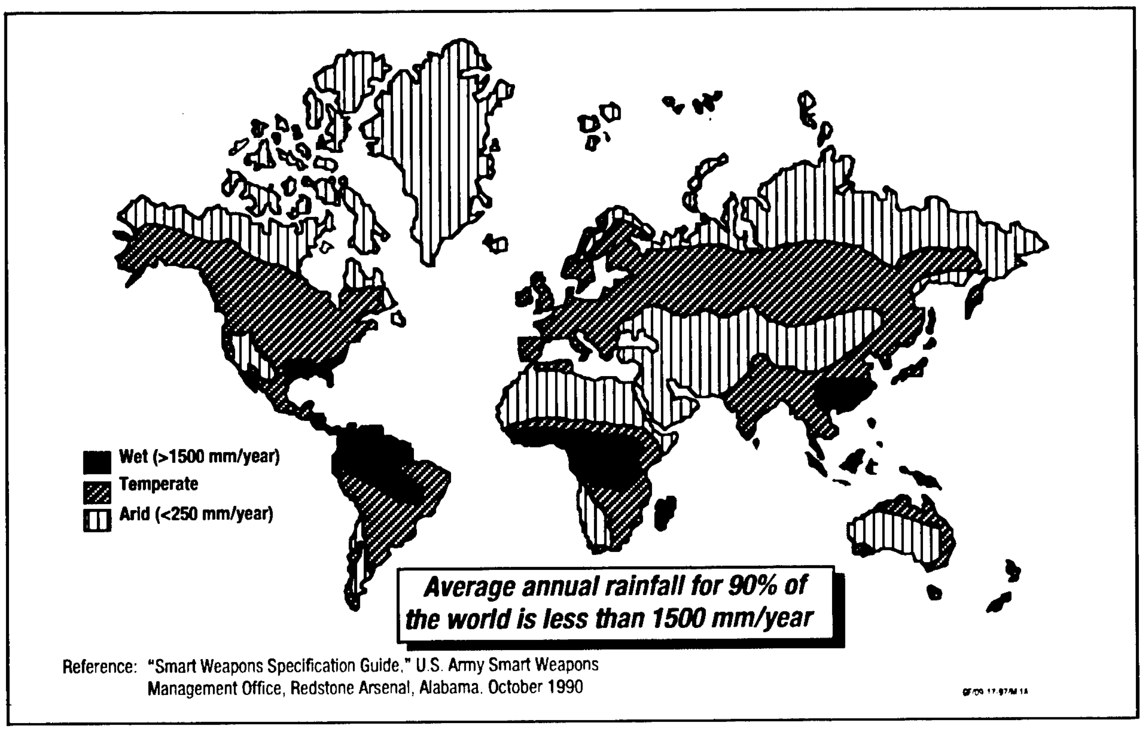


Figure 2. Rain Climatology

UTA sensor attenuation is greater for rainfall from high altitude clouds. There is a longer path length through the rain for high altitude clouds than for low altitude clouds. Figure 3 shows the probability of cloud height for the temperate, wet, and arid regions of the world's land mass. Note that clouds in arid regions tend to occur at higher altitudes while the clouds in the temperate and wet regions tend to occur at lower altitudes. Clouds tend to occur at a height of 1.0 to 5.0 km altitude.

Figure 3 also shows the probability of rain rate for a temperate region of the world that has a relatively high annual rainfall. The average probability of no rain is 80 percent for this region. The probability of rain rate less than 4 mm/hr is very high--96 percent. Also shown for comparison is an average probability of rain rate for the Middle East. The probability of no rain is very high--96 percent and the probability of rain rate less than 4 mm/hr is even higher--99 percent.

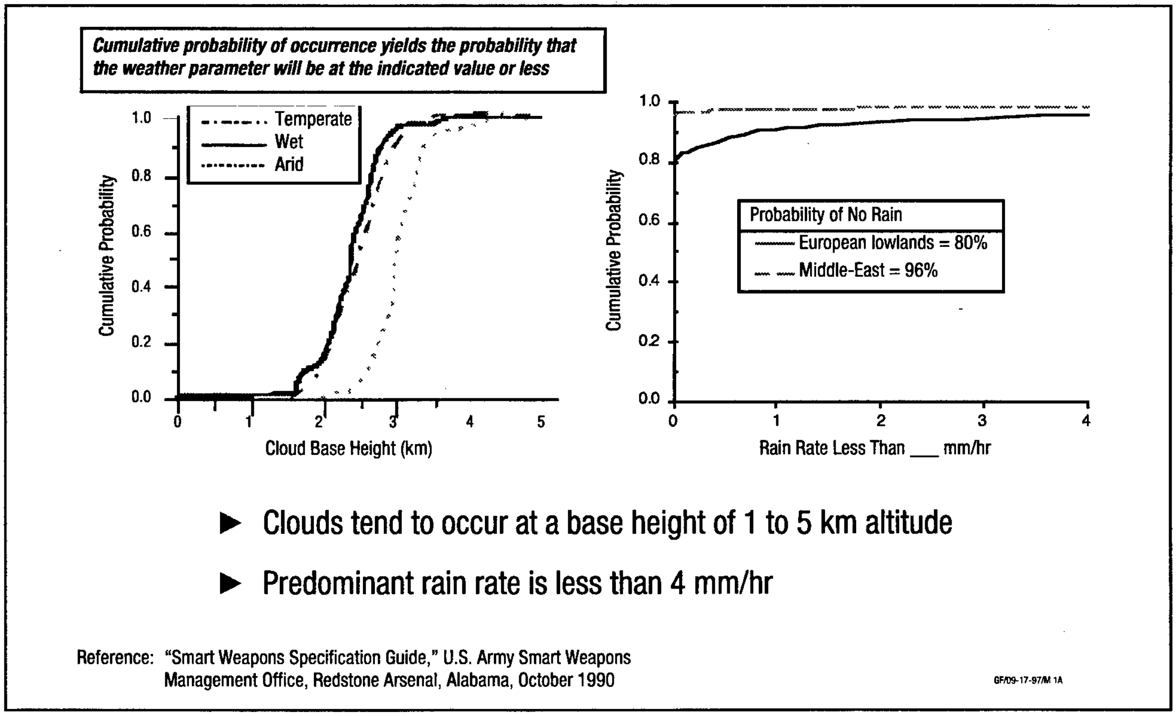
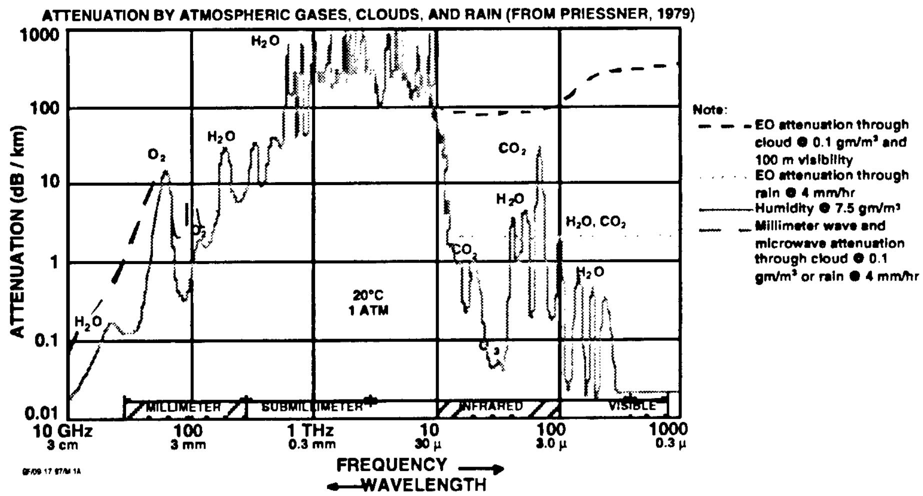


Figure 3. Adverse Weather Performance Requirements

For the purpose of this assessment, a maximum cloud base height of 5 km, a maximum cloud thickness of 2 km, and a rain rate of 4 mm/hr are considered to be cost effective requirements for UTA sensors. It would be unnecessarily restrictive to require UTA sensors to operate in 100 percent weather conditions, such as severe thunderstorms.

Figure 4 shows the attenuation versus wavelength for a representative cloud, rain rate, and humidity level requirement. Note that although passive EO sensors have one-way transmission through rain of about 50 percent per km, there is almost no transmission of an EO signal through clouds. Cloud droplets are small, about 5 to 20 microns in diameter, with dimensions comparable to the EO wavelength. The concentration is high--about 50 to 500 droplets per cubic centimeter. EO wavelengths are strongly diffracted around cloud droplets due to Mie electromagnetic scattering. However, rain drops are about 2-6 mm diameter (much larger than EO wavelengths) and cause less attenuation to an EO signal. Rain rate attenuation is due primarily to optical scattering. EO transmission through rain is a function of the size of the rain drops, rain rate, and the path length through the rain. EO passive sensors are limited from about 2 to 5 km of path length through the rain. The implications of blockage by clouds and the relatively short range in rain are that (1) the UTA will have to descend to low altitude in order to acquire target data using EO sensors, or (2) the UTA will wait for a cloud break to use EO sensors, or (3) use only the radar sensors.

The best sensors in looking down through cloud cover and rain are radar sensors. Radar sensors have negligible attenuation at frequencies below 10 GHz. At higher frequencies, passive millimeter wave sensors operating in cloud cover and rain are limited from about 2 to 5 km length of path through the clouds and rain, with the same implications as those discussed in the previous paragraph. Cloud droplets, which are much smaller than mmW wavelengths, absorb mmW radiation (much like a microwave oven). A different mechanism is responsible for the attenuation of a mmW signal through rain or snow. Rain drops and snow flakes are comparable in size to mmW wavelengths and cause Rayleigh and Mie electromagnetic scattering attenuation. Lower frequency Ku-band sensors are less affected by cloud cover and rain rate.



- EO sensors are ineffective through cloud cover
- Radar sensors have good to superior performance through cloud cover and rain

Figure 4. Signal Attenuation Due to Weather

3. SENSOR TECHNOLOGY EXPLOITATION OF THE YEAR 2007

An overall summary comparison of target sensor alternatives against UTA measures of merit is given in Figure 5. The measures of merit selected for the UTA missions are: performance in an adverse weather environment of cloud cover and rain; target resolution capability; contrast of the target to the background clutter; multi-dimensional target discriminants in the areas of polarization, temporal, and shape signatures that are used in ATR; multi-spectral discriminants across a broad range of frequency and wavelength that are used in ATRs; and weight/cost. The adverse weather measures of merit of performance through clouds and rain rate were discussed in Section 2. Figure 5 is based on the assumptions of a cloud thickness of 2 km, a cloud base height of 5 km, and a rain rate of 4 mm/hr.

	Weather			ATR					
Sensor Type	Cloud Cover	Rain Rate	Resolution	Contrast	Polarization	Temporal	Shape	Multi-Spectral	Weight and Cost
SAR	Superior	Superior	Superior	-	Superior	-	Good	Good	Average
UWB SAR	Superior	Superior	Good	Average	Good	-	Average	Superior	Average
FLIR	-	-	Good	Average	Average	-	Good	Superior	Superior
LIDAR	-	-	Superior	Superior	-	Superior	Superior	Good	Good
TV	-	-	Superior	-	Good	-	Good	Good	Superior
Passive mmW	Average	-	Average	Superior	-	-	Average	Average	Good
Combined Multi-Spectral, Multi-Dimensional	Superior	Superior	Superior	Superior	Superior	Superior	Superior	Superior	Average

Note: Superior Good Average - Poor

Combined sensors provide superior performance

Figure 5. Target Sensor Suite Performance Projected to Multi-Mission UTAs of the Year 2007

The best overall sensor for a UTA payload is probably a SAR sensor operating at a frequency in either the X-band (~10 GHz) or in the Ku-band (~17 GHz). These bands permit a small antenna size while also providing a capability to penetrate clouds and rain rate. SAR sensors have the flexibility required to cover an area search (e.g., 5 km by 5 km) for single cell target detection, then switch to high resolution (e.g., 0.3 meter) for target ID and targeting. SAR sensors also provide high accuracy profiling of the known terrain features around the target.

Although current SAR sensors have good imagery performance, their current ATR and FAR performance is much worse than the performance of a human. At the present time, SAR sensors require post-flight human analysis of the SAR imagery in order to identify targets and eliminate false alarms. This time consuming process will be alleviated in the next generation ATR that will include polarization discriminants. The additional information will be fused with the SAR imagery as well as information from the other sensors in the UTA sensor suite to greatly enhance ATR.

Polarization provides a SAR sensor with the capability to extract information on the target at long range from a single cell of data. Full polarization algorithms are under development by Boeing. Full polarization (transmit left/right, receive left/right) allows complex targets to be decomposed into elemental scatterers such as dihedrals, trihedrals, cylinders, helix, and dipoles.

The Lincoln Laboratory is also currently developing ATR algorithms based on a different approach to SAR polarization. A high resolution, polarimetric SAR called Advanced Detection Technology Sensor (ADTS) has been developed by Lincoln Laboratory under DARPA sponsorship. ADTS will collect mmW SAR polarimetric data on targets in foliage clutter. The center frequency of ADTS is 33.6 GHz and the bandwidth is 600 MHz.

Another enabling technology that allows incorporation of a SAR sensor into a weight limited UTA is the use of phased array antennas with frequency modulation continuous wavelength (FMCW) as an alternative to a conventional pulse frequency modulation (PFM) SAR. A FMCW SAR sensor requires about one eighth the peak power of a PFM SAR, completely eliminating the high power transmitter chassis. Simplified motion compensation is used which requires one fifteenth the computations--motion compensation primarily occurs in radar hardware using digital synthesis and not in the computer. Also, the lower required output of the FMCW SAR system is spread over the full bandwidth in a relatively long chirp, making a FMCW SAR more difficult to detect by the threat. The net result is a SAR that is about one fourth the weight and cost of a conventional PFM SAR.

Referring back to the Figure 5 summary comparison of UTA sensor alternatives, the next priority sensor is considered to be a low frequency ultra wide band (UWB) SAR sensor for foliage penetration. Low frequency UWB SAR has superior performance in cloud cover and rain rate while providing polarized detection of targets in foliage clutter. An example of current UWB SAR is the Swedish Coherent All Radio Band Sensing (CARABAS) VHF UWB SAR. Another example is the ERIM 200 MHz to 900 MHz UWB SAR. The ERIM UWB SAR is currently in flight test evaluation on a P-3 aircraft. Both radars use polarization.

The use of a UWB SAR to detect underground targets is also being investigated. Penetration depths of 1 to 100 meters are possible for UWB SAR sensors operating at frequencies lower than 100 MHz.

Incorporating a relatively large UWB SAR into a UTA is a design and integration challenge. Approaches include incorporating the antenna into the wing or using a leading or trailing boom as an antenna.

Referring back again to the Figure 5 summary comparison of UTA sensor alternatives, note that a FLIR sensor also complements the baseline SAR sensor. Although a FLIR sensor has no performance in cloud cover, there may be opportunities to revisit the target area if there is a cloud break during the long duration mission. The FLIR sensor provides additional multi-spectral, multi-dimensional information at shorter wavelengths. There is a relatively small increase in the sensor suite cost and weight to incorporate a FLIR sensor.

EO focal plane array sensors cover the wavelength range from ultraviolet (UV) through long wave infrared (LWIR). In the IR wavelengths, there are a number of detector materials available. Most IR FPA detectors are mated to a silicon readout circuit through indium columns, resulting in a sandwich or hybrid sensor. There is a potential problem of a mismatch in the thermal coefficient of expansion since these devices operate at cryogenic temperatures. Large IR FPAs tend to have lower yield than the simpler, more easily produced monolithic silicon based FPAs that are used in visible light TV cameras.

In the SWIR and MWIR wavelengths (1 micron to 5 microns), the leading high performance FPA detectors for post-2007 UTA application are InSb, HgCdTe, and Quantum Well Infrared Photodetector (QWIP) detectors. InSb and HgCdTe FPAs of 640 x 480 size are currently in production. In development are array sizes up to 1024 x 1024 with pitch (detector-to-detector spacing) as small as 18 microns. Figure 6 illustrates the state-of-the-art (SOTA) advancements of Boeing's MWIR HgCdTe FPAs. It is postulated that by the year 2007, HgCdTe MWIR FPAs will be in production in a 2048 x 2048 size with 10 micron pitch-performance, providing resolution that is comparable to that of the present SOTA of TV cameras.

QWIP FPAs are based on stacked thin layers of materials that form quantum wells sensitive to a broad range of MWIR and LWIR wavelengths. Each layer is only a few molecules thick, creating energy subbands where quantum effects respond to the IR incident radiation. QWIP FPAs are produced using molecular beam epitaxy (MBE), a relatively inexpensive process, and have high detector uniformity and yield. Disadvantages are a requirement for cooling down to less than 60 Kelvin and a relatively low quantum efficiency.

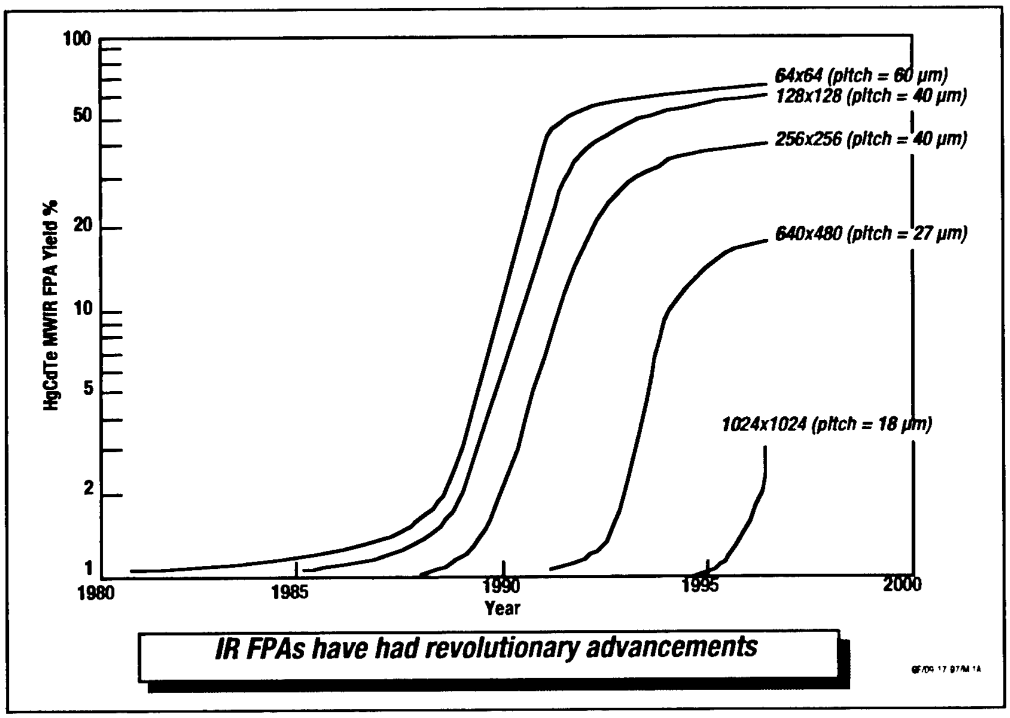


Figure 6. Example of Advancement in SOTA of IR FPAs

LWIR (8 to 12 microns) high performance tactical FPA detectors include HgCdTe and QWIP. HgCdTe LWIR devices that are currently in production have array sizes up to 256 x 256, with a pitch of about 40 microns. It is projected that by the year 2007, HgCdTe LWIR FPAs will be in production in array sizes up to 640 x 480, with 20 micron pitch. It is currently more difficult to produce HgCdTe LWIR FPAs in large array sizes due to the thermal mismatch of the larger LWIR hybrid FPA. Solutions based on a balanced composite structure are currently in development. Also in development are HgCdTe multi-spectral FPAs capable of simultaneous detection in both the LWIR and MWIR bands.

QWIP LWIR FPAs are currently in development. As mentioned in the previous paragraph, QWIP FPAs have advantages of uniformity, low thermal stress even in large size arrays, and suitability for multi-spectral applications. As stated previously, disadvantages of QWIP sensors are a requirement for cooling down to less than 60 Kelvin and relatively low quantum efficiency. Cryo cooler engines operating at temperatures below that of liquid nitrogen (77 Kelvin) are currently in development for application to QWIP FPAs. The relatively low quantum efficiency of QWIP FPAs is expected to be alleviated by technology advancements for this relatively immature technology and the use of multi-

spectral discriminants that provide enhanced detection at longer range.

Referring back again to the Figure 5 assessment of UTA sensor alternatives, the fourth priority sensor in an overall sensor suite to detect low observable targets in clutter is Laser Infrared Detection and Ranging (LIDAR), also known as LADAR. LIDAR provides unique three dimensional high resolution and temporal information (e.g., target skin vibration, target exhaust gases) that complement the passive IR sensors of a multi-spectral, multi-dimensional sensor suite. The LIDAR transmitter is usually boresighted to an IR FPA sensor that acquires and tracks the target. The capability to simultaneously measure the passive IR signature and compare it to the reflected LIDAR signature from the laser enhances the ATR performance.

A technology currently in development that will enhance the application of LIDARs is tunable lasers. Tunable LIDARs provide a broader band of wavelength for multi-spectral ATR.

Target designation is a mission that can be addressed by a LIDAR sensor. The UTA sensor suite would hand off target coordinates to the LIDAR for tracking and laser designation. Laser guided weapons launched from manned aircraft platforms would then home on the laser designated target with precision accuracy. It is postulated that UTAs that are designated to carry weapons as part of a primary mission will not occur until after the year 2007 time frame. An operational capability in the year 2007 was used as an assumption in conducting the technology assessment for this paper.

Referring back again to Figure 5, the fifth priority target sensor of a UTA target sensor suite would be a visible light multi-spectral camera. Advantages of a TV sensor include high resolution due to the short wavelength and an additional discriminant of the polarized reflection of sunlight. Although a TV sensor is not effective in cloud cover or at night, a long duration flight UTA could perhaps revisit the target area when appropriate.

Visible detectors are a more mature technology than IR detectors. The detectors are fabricated from silicon, using many of the processes already developed for commercial integrated circuit manufacturing. The visible detector FPA and readout circuitry are usually fabricated in a one piece, monolithic sensor. Large size visible detector arrays are currently in development with array sizes larger than 5000 x 5000. The current SOTA in center detector spacing (pitch) for visible FPAs is 8 to 12 microns.

Referring back to Figure 5 for a final time, note the strengths and weaknesses of passive mmW sensors. Passive mmW sensors have an advantage over EO sensors in their capability to see through cloud cover and the high contrast of metal objects in the mmW spectrum (see Figure 7). Advantages over active RF sensors include lower noise and the avoidance of radar glint. The cold sky (about 35k) is reflected by metal objects at mmW frequencies while the temperature of terrestrial object clutter is about 300k. Current radiometers can typically detect differences in temperature of 1k and radiometers are in development that will detect differences in temperature of 0.1k, providing a very high signal-to-noise ratio of more than 300 to 1.

Passive mmW cameras similar to video cameras are under development by TRW. Cameras have been ground tested at 60 GHz, 65 GHz, 89 GHz, and 95 GHz frequencies. Array sizes up to 40 x 26 elements have been produced. Apertures that have been produced to date range in diameter from 0.4 meter to 0.6 meter. Frame rate demonstrated to date is 17 Hz. Airborne flight tests are planned in late 1997 to flight demonstrate a passive mmW sensor.

Disadvantages of passive mmW sensors include relatively low resolution compared to EO and SAR sensors and attenuation in cloud cover and rain rate. However, passive mmW technology is relatively immature and future passive mmW sensors of the post-2007 time frame will have distributed apertures for operation as a high resolution interferometer. Distributed apertures consisting of ten or more widely spaced apertures could provide an effective aperture that would be comparable to the wing span of the UTA.

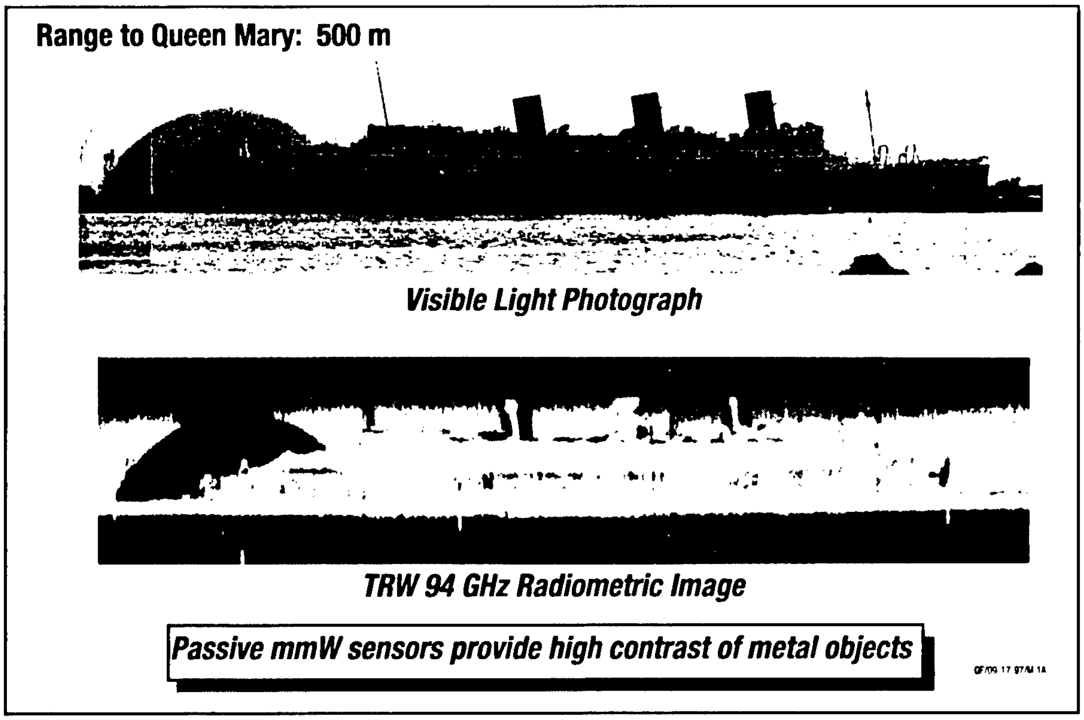


Figure 7. Passive Imaging mmW View of Queen Mary and Spruce Goose Dome

Sensor tracking errors due to the error slope of a conventional hemispherical dome are a traditional problem for EO and RF sensors. Small imperfections in the shape of a hemispherical dome greatly affect the tracking accuracy. An approach that alleviated the problem for EO and RF domes on ballistic missile defense interceptors is to use a flat window as a dome. The error slope of the flat window is nearly negligible compared to a traditional curved hemispherical dome. Another advantage of a flat window for sensors is reduced observables. A grid or slotted film over the window can be tuned to be IR or RF transmissive in the wave length or frequency of interest and RF reflective for out-of-band frequencies. This results in reduced RF back scatter to threat radars, providing reduced radar cross section (RCS) for the UTA. Figure 8 shows experimental and predicted results of the RCS of a treated flat grid pyramidal shaped set of windows compared to a conventional treated hemispherical dome. The 1.5 to 1 length-to-diameter ratio pyramidal flat grid windows provide more than -20 dB reduction in RCS compared to a conventional 0.5 to 1 length-to-diameter ratio hemispherical dome.

As mentioned previously, the current SAR systems generate a tremendous amount of data, driven by requirements for high resolution and large swath widths. The extension of SAR polarization will drive data rates even higher. Communication systems and data links handling capability will need to increase in the future to handle the increased amount of on-board data. Future data transmission systems will use split data links to relay satellites, ground stations, manned aircraft, or other UTAs. UTA data transmission and storage rates SOTA at the present time are of the order of 50 to 100 Megabits per second.

Phased array antennas are in development that provide high data rate (~600 Megabits per second) and flexibility for a UTA to rapidly and efficiently communicate with satellites, ground stations, manned aircraft, or other UTAs. Phased array antennas may also be applicable to agile, highly accurate electronic signal intelligence (SIGINT). A concern in applying phased array antennas to an intel mission is the mission may require operation over a very broad band (e.g., 500 MHz to 35 GHz) that is outside the SOTA of phased array antennas for UTAs.

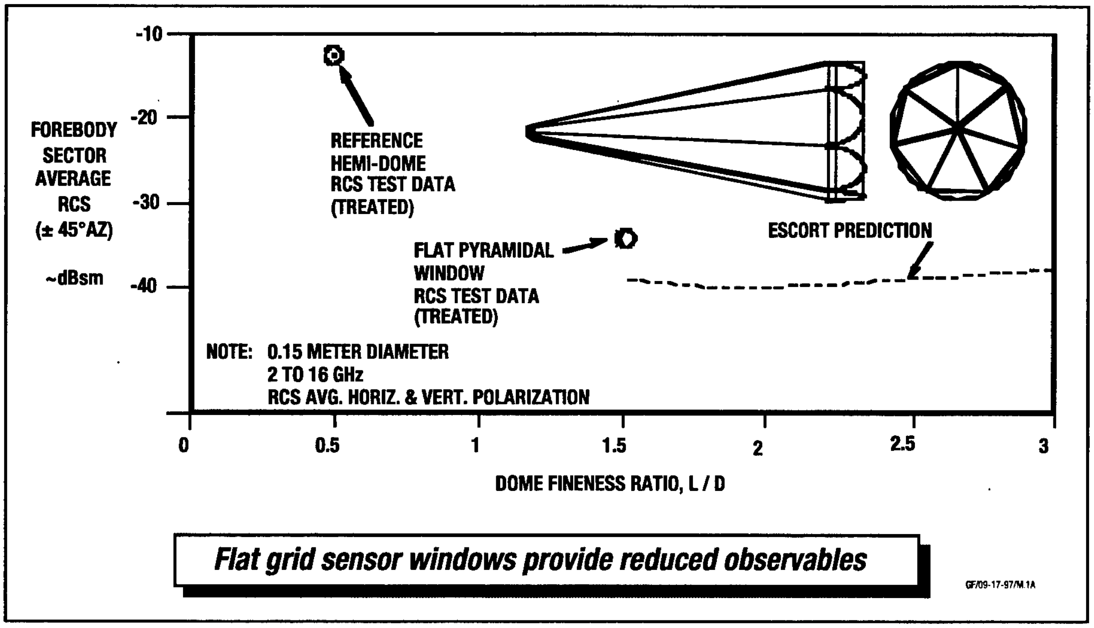


Figure 8. Flat Grid Windows for Sensors

Boeing is developing a family of low cost, high performance phased array antennas for airborne communication (Figure 9). Planar devices have been developed in the SHF-band, Ku-band, and Ka-band. Airborne flight tests have been conducted on military, commercial, and general aviation aircraft.

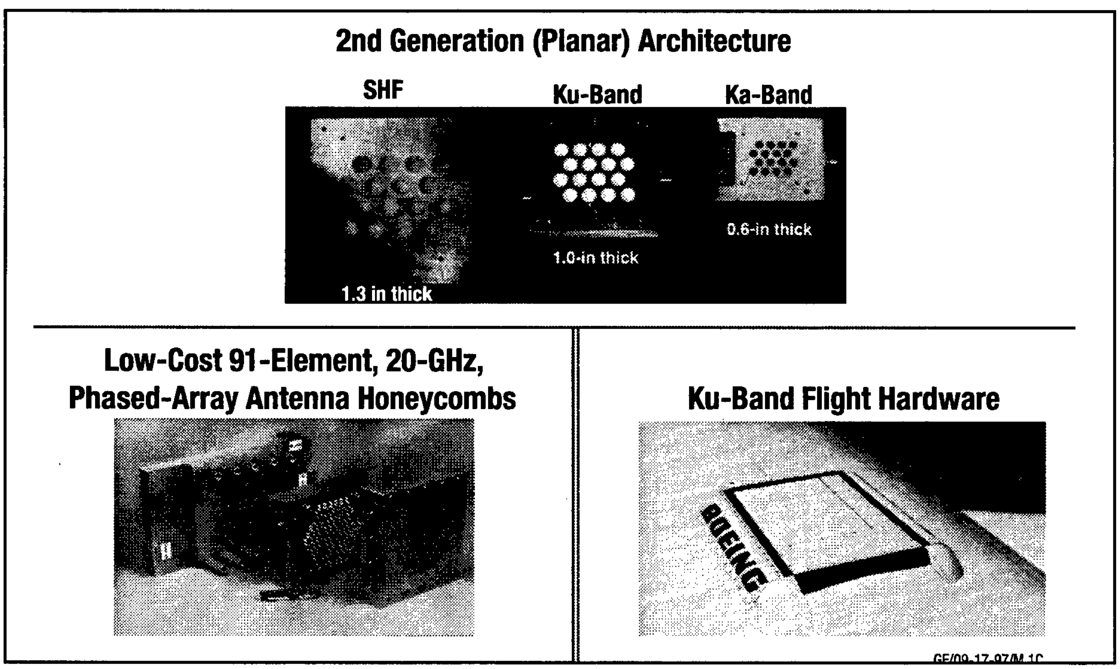


Figure 9. Boeing Phased-Array Family for Mobile Communications

Precision targeting with accuracy better than 3 meters will require high performance navigation sensors. The current Global Positioning System (GPS) receivers operating in a military P(Y) code have an accuracy of approximately 6 meters. Recent advances in using GPS in the Wide Area GPS Enhancement (WAGE) mode, differential mode, or relative mode, combined with SAR precision mapping, have the potential to provide target location with an error less than 3 meters.

Figure 10 illustrates examples of GPS receivers and inertial sensors that are currently being used in GPS/INS navigation. Inertial sensors that are currently available include those based on ring laser gyros, fiber optic gyros, and digital quartz gyros. An emerging technology is a Micromachined Electro-Mechanical Sensor (MEMS) that is fabricated from a single piece of silicon. Good performance is achieved in a small size, low cost package. Between 2,000 and 5,000 devices can be produced on a single five-inch silicon wafer.

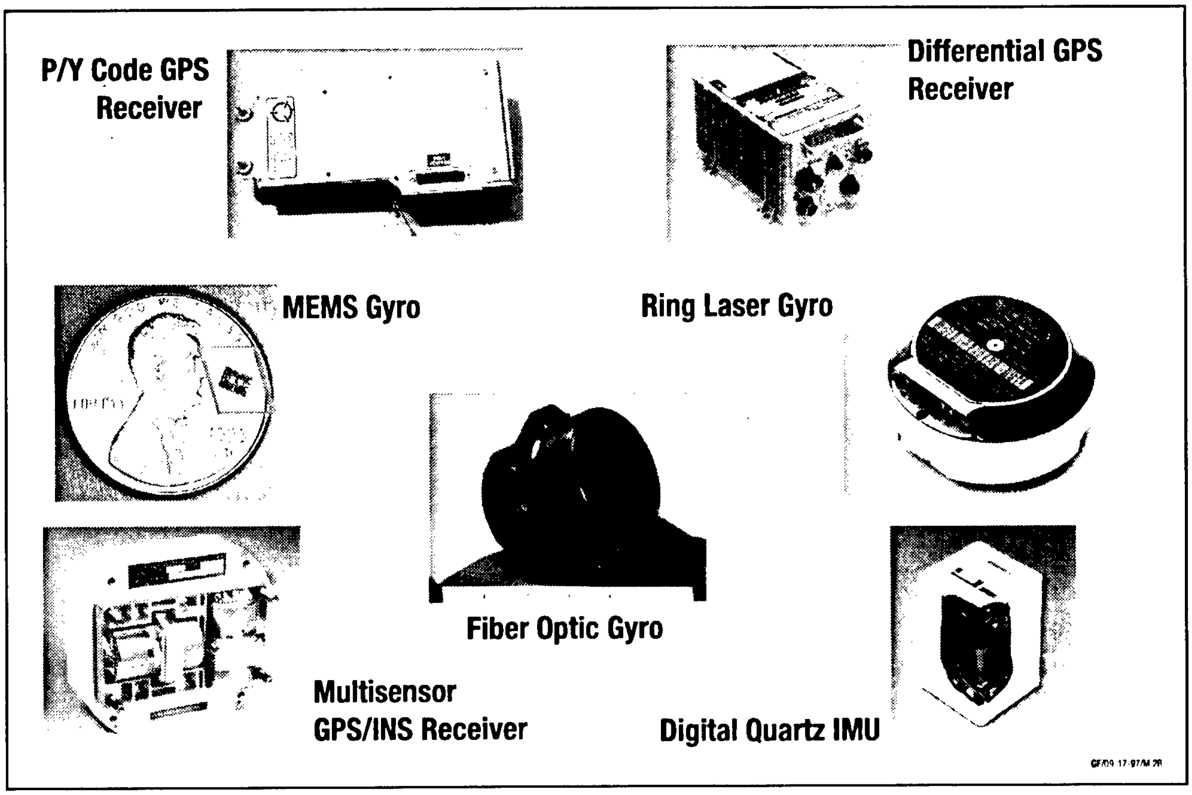


Figure 10. Example of Navigation Sensors

Figure 11 illustrates the advantages of GPS/INS integration. Benefits of GPS/INS integration include high precision position and velocity measurement, reduced sensor noise, reduced jamming susceptibility, and attitude measurement capability. A UTA operating at altitudes higher than 8 km with a modern GPS receiver will have low susceptibility to jamming. The availability of GPS to continuously update the inertial system allows the design trades to consider a lower precision and less expensive INS, while maintaining good navigation accuracy and anti-jam (A/J) performance.

Future GPS/INS receivers will be based on a centralized Kalman filter that processes the raw data from all of the sensors (e.g., SAR, GPS receiver, INS). Tightly coupled GPS/INS is more robust against jamming because it is able to make pseudo-range measurements from three, two, or even one satellite if one or more of the satellites are lost.

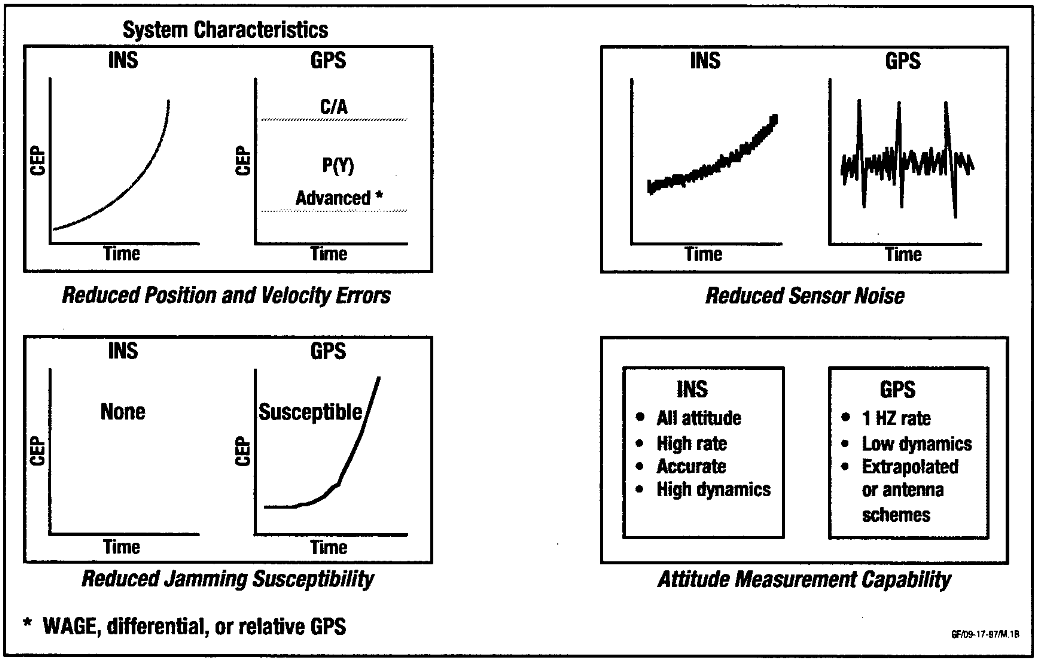


Figure 11. Why GPS/INS Integration?

The 6 meter GPS standard accuracy is improved when multiple GPS measurements are combined in a Kalman filter that provides a calibration of GPS and INS errors. An example shown in Figure 12 is a Conventional Air Launched Cruise Missile (CALCM) demonstration called Precision On-Board GPS Optimization (POGO), where a better than 3 meter accuracy was demonstrated. Ionospheric errors, tropospheric errors, satellite clock errors, satellite ephemeris errors, and other errors were reduced through the use of a centralized sixty state Kalman filter.

Error Sources	Standard GPS	POGO Demo	Source of Improvement
User Range Error Satellite Ephemeris = 4.0m Satellite Clock = 3.0 m	5 m	URE = 2.0M 1.8 1.0 1.0	• WAGE Phase 1 • Accuracy Improvement Initiative (AII) • WAGE - complete • Block IIR satellites
Ionosphere	2.3	1.0	• Dual-frequency Receiver • Special algorithm based on phase
Troposphere	2.0	0.5	• Real-time pressure and temperature measurements • Accurate modeling
Multipath	1.2	0.4	• Low missile multipath • Phase use as well as code
GPS Receiver	1.5	0.5	• New technology
RSS Total	***6.2M***	***1.66 - 2.4M***	• URE dependent

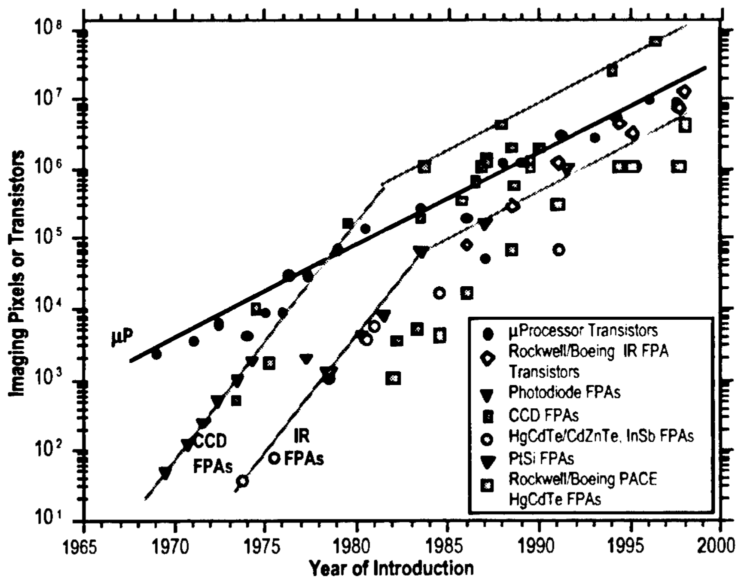
URE = User Range Error

GF/09-17-97/M.1B

Advanced GPS provides precision navigation for targeting

Figure 12. CALCM Precision On-Board GPS Optimization (POGO) Demonstration

A final enabling technology for UTA sensors is sensor electronics. Figure 13 illustrates the rapid growth in electronics for FPAs. The exponential growth in micro processor transistors for FPAs has about a three-year lead on the number of pixels available in IR FPAs and about a four-year lag on the number of pixels available in visible FPAs. There is no sign that the growth rate will slow down. Similar results also apply to memory chips, for example, 256 Megabit dynamic ram memory chips are currently in development



Electronics for sensors have had revolutionary advancements

Reference: Kozlowski, L. J., "Impact of Submicron CMOS on IR FPAs", presented at the 1997 Meeting of the IRIS Specialty Group on Infrared Detectors, July 1997

Figure 13. Example of High-Speed, Lightweight Electronics Trend for EO Sensors

4. CONCLUSIONS

Enabling capabilities, performance enhancements, and enabling technologies have been identified for UTAs in the year 2007 time frame. The sensor related enabling capabilities and performance enhancements are:

- Multi-spectral, multi-dimensional sensors that provide real time, low FAR ATR and real time, precision targeting
- Flat windows that provide reduced observables

The sensor enabling technologies are:

- Polarized FMCW SAR sensors for detection, ID and targeting of low observable targets in clutter
- Low frequency, polarized UWB SAR sensors for detection, ID and targeting of low observable targets in foliage
- High resolution, multi-spectral FLIR sensors for ID of low observable targets in clutter
- Tunable multi-spectral, three dimensional, temporal LIDAR sensors for ID and targeting of low observable targets in clutter
- High resolution, multi-spectral visible sensors for ID of low observable targets in clutter
- Moderate resolution, high contrast passive mmW sensors for ID of low observable targets in clutter
- Flat grid windows for reduced observables and low error slope
- Phased array antennas for high agility, high data rate comm
- Agile, broad band, high accuracy electronic SIGINT
- Precision GPS/INS navigation and targeting
- High speed, light weight electronics

5. REFERENCES

Schneider, Stephen H., "Encyclopedia of Climate and Weather," Oxford University Press, 1996.

"Smart Weapons Specification Guide," U.S. Army - Smart Weapons Management Office, Redstone Arsenal, Alabama, October 1990.

Priessner, 1979

U.S. Air Force Science Advisory Board Sensors Panel, "New World Vistas Air and Space Power for the 21st Century - Sensors Volume," 1996.

Kozlowski, L. J., "Impact of Submicron CMOS on IR FPAs," presented at the 1997 Meeting of the IRIS Specialty Group on Infrared Detectors, July 1997.

System Layout of an Unmanned High Altitude Aircraft for Certification and Flight in Civil Airspace

I. Papachristofilou
L Komninon 66
55236 Panorama, Thessaloniki
Greece

and

P. Kaempf[1]
Prof. Dr. O. Wagner[2]

1 Introduction

Several unmanned air vehicles (UAVs) are currently in operation or under development, and predictions for the future indicate an expansion in the tasks that will be covered by UAVs. With missions conceivable both in the civil as well as military sectors, UAVs are expected to be procured and operated in increasing numbers in the immediate future. However, besides the technical challenges associated with unmanned flight, the issues of certification and rules of operation of unmanned aircraft in non-restricted airspace need to be addressed.

Flights of unmanned aircraft are currently taking place within reserved airspace with only few exceptions where UAVs have been allowed to enter open airspace under special precautions. The potential of unmanned aircraft can only be exploited if such restrictions are lifted and they are certified to operate along manned aircraft. To reach such a point, formulation of explicit certification requirements on the system design of the aircraft is required, as well as a series of flight tests to validate the concept of safe use of unmanned aircraft in non-restricted airspace.

Although such regulations do not exist at the moment, airworthiness and air traffic control authorities have already started examining the issues involved and are expected to issue guidelines covering unmanned flight in the near future. Based on information available from the above mentioned authorities, the main characteristics of those regulations can be described at the present time. Moreover, the implications on the system design of unmanned aircraft can be highlighted, showing the parameters that are to influence future designs.

In our view the least complicated route to the operation of unmanned aircraft in civil airspace can be explored with a subsonic high altitude reconnaissance platform. Here the relocation of the pilot to a ground station offers the highest benefits, creating a strong rationale for the development of such a craft. At the same time, only a limited number of additional subsystems are necessary to facilitate flight in open airspace, which will be demonstrated by means of a recently concluded conceptual design of an unmanned high altitude aircraft.

2 Scenarios for unmanned aircraft

The range of unmanned aircraft which are technically feasible within the coming decade can be divided into three groups,

[1] Conceptual Design Analysis, Daimler-Benz Aerospace AG, Ottobrunn
[2] Lehrstuhl für Flugmechanik und Flugregelung, TU München

Paper presented at the AGARD MSP Symposium on "System Design Considerations for Unmanned Tactical Aircraft (UTA)", held in Athens, Greece, 7-9 October 1997, and published in CP-594.

concerning the difficulty of operation in civil airspace:

- Unmanned high altitude reconnaissance platforms with flight profiles above the current airways (above FL 500) which need to fly in mixed traffic only during ascent and descent. Since their use lies predominantly in the areas of peacekeeping and crisis control and involves flight over long distances, the need for certification for flight in civil airspace is most pressing in this case.
- Unmanned autonomous reconnaissance platforms which are operated at medium to low altitudes in the target area and cruise above FL 200. Here a more accurate navigation system is necessary, and the system has to cope with adverse conditions (maneuvering of the airframe, jamming by hostile forces).
- Unmanned tactical aircraft to fly strike and/or attack missions in a conflict. Even though this class of aircraft operates predominately over hostile territory, it will be dispatched from friendly bases and therefore fly partially over friendly territory. Also, to minimize collateral damage, the system accuracy and reliability should match that of current manned aircraft.

To compensate for the missing human on board, all these aircraft need a system architecture which allows to limit the failure probability of the whole system to the same low values which are placed on manned aircraft by the civilian certification authorities. This architecture can be explored most easily in a high altitude UAV and then transferred to more sophisticated types of UAVs.

3 Certification requirements

Since no specific regulations exist, the civil certification basis for small and medium-sized UAVs (below 5.7 tons take-off weight) is JAR Part 23, which has to be modified in those areas that do not apply to unmanned aircraft. These modifications have to be defined by the UAV manufacturers in cooperation with the airworthiness authorities.

The most important factors influencing the system layout of the aircraft are reliability and failure probability. The requirement set by airworthiness authorities for granting civil certification is that the probability of a catastrophic failure occurring which could endanger lives on the ground shall be 10^{-9} per flight hour or less. The figure is identical to that of civilian aircraft, whereas the failure probability of aircraft certified under military procedures are typically in the order of 10^{-7} per flight hour. If a different subsystem exists to prevent a catastrophic failure in case of a subsystem malfunction, it is allowed to multiply the probability of occurrence of such a condition with the probability of failure of the secondary subsystem to reach the desired figure of 10^{-9}.

In order to facilitate flights of UAVs in non-reserved airspace, Air Traffic Control Authorities require that there should be no difference apparent to them between a manned and an unmanned platform. This implies that ATC must be in continuous two-way contact with the UAV operator in the ground control station, regardless of the latter's physical distance to the aircraft. The operator must be in a position to change the UAV's flight path in accordance with the instructions received from ATC.

Flights of unmanned aircraft should preferably take place under IFR conditions. It shall be taken into account that the aircraft are also to fly in airspace sectors where VFR flights are conducted, requiring compliance with the avoidance rules. The latter applies particularly to the take-off and landing phases and during flight segments conducted at low altitude. Options currently under study by authorities include the temporary placement of restrictions in airspace sectors used by UAVs for their initial climb and final descent phases or the installation of a visual airspace surveillance system on

board the aircraft, which would downlink pictures to the ground control station.

Due to the limited range of high-bandwidth radio links at low altitude, close operator control can not be ensured during emergency landings. While manned airplanes can lower the hazard to lives on the ground by pilot interaction, this option is not available to UAVs. Therefore, the flight plan of the UAV shall include emergency flight profiles and recovery areas to cover for the cases of a critical system malfunction that prohibits the aircraft from returning to its take-off airfield. In conjunction with the above, it becomes necessary to include a flight termination system that shall be independent of the propulsion and flight control systems of the aircraft and provide the means for a controlled descent within the designated areas. Systems being studied include a selfdestruction system or a parachute recovery system.

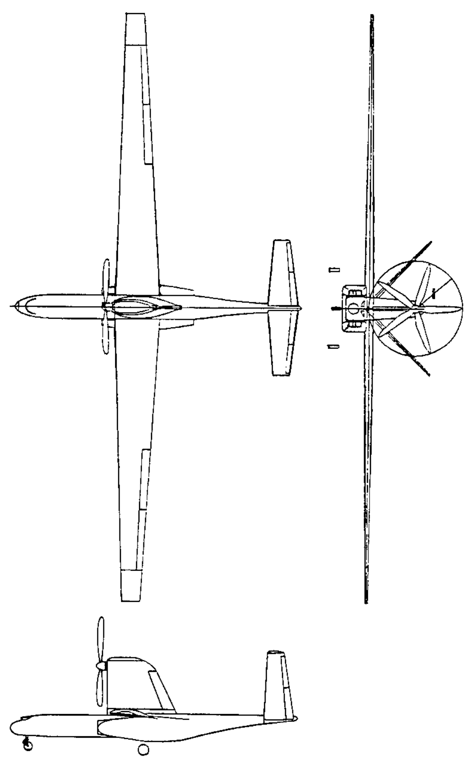
Finally, regarding the qualification of the ground operators, a CPL (commercial pilot's license), IFR and type rating are viewed as sufficient. The definition of the type rating will include the unmanned characteristics of the aircraft and its exact aspects shall be addressed in the phase leading to aircraft certification.

4 Unmanned High Altitude Aircraft

To study the technical and certification aspects of UAVs, a preliminary design for an unmanned high altitude aircraft was completed during 1996 at Daimler-Benz Aerospace in Ottobrunn, Germany. The main performance goal of the design was for the aircraft to be able to reach an altitude of 18 km carrying a payload of 500 kg and loitering for 8 hs. A second mission was specified for 24 km altitude with an on-station time of 1 h while accommodating an 100 kg payload. The aircraft burns standard fuel and it's structure is designed for a minimum lifetime of 6000 hours. To maximize operational flexibility, the aircraft can be disassembled and fitted in a standard container (ISO 688 1AA).

Apart from the above, a series of operational requirements influenced the system layout of the aircraft. The aircraft should be certifiable by civilian airworthiness authorities and be equipped for flight in civil airspace. Take-off and landing should be conventional with operation feasible from standard runways. The aircraft should be able to operate either in autonomous or remotely controlled mode throughout the flight, including the take-off and landing phase.

The resulting aircraft is a single-engine, high-aspect-ratio conventional configuration with a retractable three-cycle landing gear. It has a take-off weight of 2380 kg, 30 m^2 wing area, 24 m wingspan and is powered by a turbocharged six-cylinder piston engine which drives a five-bladed propeller with a diameter of 4 m. Payload is carried in a dedicated bay in the forward part of the fuselage, allowing the installation of various modules covering for the diverse missions to be flown by the aircraft.



5 Control System Layout

The requirement for civil certification determines the redundancy level in the system layout. As already mentioned, the airworthiness authorities require a catastrophic failure probability resulting in fatal injury to people on the ground of less than 10^{-9} per flight hour. As mentioned above, the UAV is not in a position to perform a safe landing at locations other than ground station equipped airfields. Therefore, it is not possible to assume that in case of a critical system malfunction that degrades the performance of the aircraft to a level where an emergency landing is essential, the aircraft will deviate to any nearby airfield or uninhabited area and perform a safe and secure landing. Even if the aircraft has the capability to fly and land autonomously, Air Traffic Control objects to the case of a UAV approaching and landing at a civilian airfield where no ground station is located. The reason lies in the extreme limited capability to alter the aircraft's flight path during landing.

To illustrate the problems associated with the above, an example shall be given. It is assumed that a single-engined UAV suffers an engine failure. If the probability for this is 10^{-4}, a figure of 10^{-5} is then required for the failure rate of the whole system to descend safely within a predesignated area. With the exception of the cases where the engine failure happens at an altitude and distance to the take-off site that allows the aircraft to return in glide mode, emergency procedures need to be worked out to cover the remaining situations. Those emergency procedures would in most cases lead to the activation of a flight termination system over a predefined area agreed upon with ATC prior to take-off. Those areas have to be listed in the flight plan and are chosen in order to minimize danger to people on the ground.

It should be stressed that integration in the aircraft of a flight termination system, which is allowed to be included in the safety analysis, allows the fulfillment of the strict requirements for hazardous failure probabilities. In combination with a highly reliable navigation and flight control system and a highly reliable datalink, the flight termination system can be literally viewed as the "joker" that helps reach the latter, by multiplication of the probabilities for critical failure and danger to people on the ground.

The individual systems proposed for the unmanned high altitude aircraft highlight the direction which will be followed in future designs having as a target to accomplish a civil certification and permission to fly in non-restricted airspace. A description of those systems is given below:

5.1 Flight Control and Navigation System

The flight control computer and primary navigation equipment require a quadruplex architecture which can tolerate up to two failures of single lanes. This is derived from the mean-time between failure (MTBF) figures of similar systems that lie in the order of 3000-5000 hours. The adverse result of this configuration is the escalating cost and mass of the subsystems.

The navigation suite is based on inertial systems (INS) that are updated in flight by satellitebased navigation systems, like GPS. Options include the use of combined GPS/Glonass receivers or the new GPS Guidance Package (GGP). The latter couples a miniature GPS receiver with an inertial measurement unit based on fiber optic gyroscopes, reducing cost and mass considerably over current INS/GPS packages. Further equipment available on board are a quadruplex air data system, a duplex radar altimeter and optionally an ILS-antenna.

5.2 Collision Avoidance

During the UAV's flight below the upper limit of VFR air traffic, the avoidance rules need to be respected. Although the aircraft lacks the classical "see and avoid" capability of manned aircraft, this particular capa-

bility can be restored to a great extent by technical means. The airspace around the aircraft will be scanned by cameras with their images transmitted in real-time to the operator in the ground control station. The operator uses those images for identification of potential dangers and then steers the aircraft in accordance with the avoidance rules.

The airspace sector that has to be covered is 220° in azimuth and 60° (+40°/-20°) in elevation. This sector is covered by three cameras installed in fixed positions in the nose of the aircraft, while a fourth stabilised camera is used to focus on detected aircraft and tracks their flight. Images are transmitted via videolink to the ground station out to a maximum range of 100 km.

Furthermore, it is foreseen to install TCAS (Traffic Alert and Collision Avoidance System) in the aircraft. The system is viewed as necessary given the operational environment of the aircraft. An issue that has to be resolved in cooperation with certification authorities and ATC is whether the flight control computer will be authorised to undertake evasive maneuvers at any point during the flight when a collision threat is identified. The alternative would be to place this responsibility on the ground operator who will be informed and act via datalink.

5.3 Datalink

The two-way datalink connection between the aircraft and the ground station is needed for continuous monitoring of the flight, modifications to the flight path and remote control of the aircraft. A further feature to be incorporated is voice relay between ATC and the ground operator via the aircraft in order to allow smoother integration into air traffic, not requiring other provisions for communication between ATC and ground station.

The resulting transmission rate reaches peak values of 35 kbit/s for the downlink and 25 kbit/s for the uplink. The datalink requirements of the payload are not included in these figures.

Flight data downlink and command uplink are implemented on the primary datalink which operates in the upper UHF band (around 500 MHz). The link is limited to line-of-sight (LOS) connections between aircraft and ground station. The maximum achievable range is 250 km while flying at 18 km and 312 km at 24 km altitude. A duplex installation is planned for the primary datalink resulting from certification requirements.

To overcome the LOS limitations, a satellite antenna is installed in the aircraft. This solution is favored over the use of multiple ground stations or relay aircraft during long-range flights. A connection via commercial channels, such as INMARSAT, allows for monitoring of the flight and reprogramming of the autopilot. Remote control is not feasible due to the time lag associated with the increased path length and the higher bit rates.

5.4 Flight termination system

The flight termination system consists of a parafoil with an area of 85 m^2, a drogue chute for parafoil deployment and a steering unit. Installation in the particular aircraft is in the upper part of the pylon to the rear of the gearbox. Power for the system comes from a 30 Ah/28 V battery. The steering unit pulls the trailing edges of the parafoil with small servo motors, thus allowing maneuvers to be conducted. The minimum deployment altitude is 800-1000m in order for the parafoil to inflate properly. The installed radar altimeter feeds data to the steering unit in order for the latter to initiate a flare maneuver close to the ground, reducing sink rate to 2-3 m/s. Overall system mass is 36 kg, representing 1.5% of MTOW.

The follwing table lists the mass of all items which are needed to fulfill the requirements for civil certification:

System	Mass [kg]
Flight Control Computer	30
Navigation System	45
Radar Altimeter	3.1
ILS	4
TCAS	16.5
Cameras	28.5
Air Data System	22
Videolink8Datalink	69.2
Flight Termination System	36
Installation	28.5
Power Supply	47
SUM	337.8

5.5 Ground Control Station

The ground station is the control part of the system that allows unmanned operation of the aircraft. It performs the following main tasks:

- remote control of the aircraft
- monitoring of autonomous aircraft operation
- modification of flight path (incl. authority to activate the flight termination system)
- monitoring of system status
- interface to air traffic control authorities
- payload operation (incl. capability for real time payload data evaluation)
- aircraft servicing at unprepared locations

Two operators will be performing the tasks in the ground station. The senior operator is responsible for monitoring, modifying and controlling the aircraft flight. His operator console will be similar to that of an aircraft cockpit. The second operator is responsible for the communication links, the interface with ATC, overall monitoring of system status and payload operation. To increase overall system flexibility and reliability both operators are to be crossqualified to perform pilot-flying and pilot-not-flying tasks. The option for a third operator who will either relieve one of the primary operators during long missions, or operate the payload from a separate console is also included in the design.

The GCS is integrated in a standard ISO 688 1C container to ease handling for transportation and will be equipped with ventilation and air-conditioning systems. A chemical toilet, water and food supplies are also to be installed, considering that flight time of the aircraft exceeds 10 hours.

A small crane for assembling and disassembling the aircraft, a repair shop and a mast antenna for the LOS connections to the aircraft are integrated in the GCS.

The GCS should be located in the vicinity of the runway in order to ensure unobstructed line-ofsight connections to the aircraft during taxiing, takeoff and landing. Power for the GCS can be supplied from an auxiliary power unit near the GCS or from an external source. Telephone links will also be needed as a backup; direct telephone connection to ATC is specified for operation of unmanned aircraft.

6 Aircraft operation

The specifications set for operation of the unmanned high altitude aircraft can be characterised as very demanding but also indicative of the requirements on such craft in the future. The aircraft has to be capable of flying autonomously during all phases of it's flight including the capability of automatic take-off and landing. The ground operator has to be able to modify the flight up to establishment of remote control. The above have to be fulfilled regardless of the actual distance between aircraft and ground station.

Automatic take-off is conducted using Differential-GPS signals or the ILS localiser

(if available) for course steering coupled with the radar altimeter for control after rotation. In the case of remote control the operator uses flight data received via the datalink while having the camera images linked to him in real-time as a visual aid.

In a similar way the operator lands the aircraft utilising datalink information and camera images. In this case, data from the radar altimeter is very important for initiation of the flare maneuver since the operator does not have a stereoscopic view of the approach. Automatic landings can be performed with DGPS signals coupled with the data from the radar altimeter.

The flight is under IFR conditions with the climb, cruise and descent phases flown by the autopilot, which can be reconfigured by the ground operator. The latter can take over remote control of the aircraft only while in LOS range to the aircraft. Separation to VFR traffic at low altitudes is accomplished by downlinking camera images of the surrounding airspace to the ground station. This feature is not necessary at higher altitudes, where separation to IFR traffic is maintained by ATC, having the TCAS as backup.

The absence of anti- and de-icing equipment on the aircraft means that flight through clouds ought to be avoided. In order to detect clouds ahead of the aircraft's flight path, a cloud detector in the form of a laserscanner is installed in the aircraft's nose. It can detect clouds out to ranges of 10 km giving sufficient time to request a new flight vector from ATC.

7 Flight Testing

The flight testing phase leading to the certification of unmanned aircraft is a critical issue as it involves elements new to the certification process. A step-by-step approach based on the current project will be highlighted in the following and shows the general course to be followed in future projects.

Prior to commencement of flight testing, the certification process has to be initiated. This will include all the steps necessary for granting a temporary airworthiness certificate but also a number of new items. These include the modifications required to JAR Part 23 with respect to unmanned aircraft the demonstration of proper datalink functioning and the qualification of the ground operators.

Flight testing would initially take place at close ranges to the ground station and under remote control. Envelope expansion and in this particular case mainly over altitude as well as autonomous flight are to be performed during the next phases. All these flights are to take place in restricted airspace while the presence of a chase plane (not at very high altitude) will be required.

Final validation of the complete system will include a number of flights under actual operating conditions in predefined sectors of non-reserved airspace and mainly over uninhabited areas (issuing of a NOTAM will be necessary). The amount of flight testing required is an issue to be decided in cooperation with airworthiness authorities and is expected to differ from case to case.

8 Conclusions

The main conclusions with respect to the certification of unmanned platforms can be summarised in the following points:

- The potential of UAVs and the need for regulations are recognised by authorities
- A military certification will be easier to achieve than a civilian one
- Clear definition of emergency procedures and systems is required
- It is technically feasible to fulfill the requirements of the certification authorities
- The reliability of several subsystems needs to be raised above the level currently required for manned aircraft, otherwise high redundancy levels are re-

quired to meet the demanding certification requirements

- A Flight Termination System, preferably a parachute, needs to be installed to ensure the required low probability of disastrous malfunctions

The real test for UAVs with respect to the above issues will come when large platforms such as those currently under development become operational. Formulation of specific regulations is expected to take place in the next few years opening the way for the increased use of unmanned platforms.

NOTE: The conceptual design of the unmanned high altitude aircraft was performed within the framework of the ECATA-Junior (European Consortium for Advanced Training in Aerospace) program. The lead author would like to express his acknowledgments to the organisers and supervisors, to all the persons who contributed to the project and to his colleagues Ferry van Ruijven, Daniele Fanteria and Matthias Nitsche.

Drone hypersonique pour des missions de reconnaissance en profondeur

L.Serre
Office National d'Études et de Recherches Aérospatiales
BP 72
92322 Châtillon
France

1. Sommaire

Le concept d'emploi d'un drone hypersonique évoluant à très haute altitude est analysé. On montre que sa mise en oeuvre ouvre la voie à une importante classe d'information qui est difficilement accessible par d'autres moyens. On montre également que le choix des senseurs est fortement couplé avec le dimensionnement du véhicule, et doit, à ce titre, être pris en compte dès le stade de l'avant-projet pour finaliser les grandes options.

2. Introduction

Les applications actuellement revendiquées pour les drones visent le plus souvent le renseignement tactique sur le champ de bataille, ou la surveillance sur zone frontière en stand-off. Ces concepts subsoniques sont assez vulnérables, et ne disposent pas de capacités de pénétration suffisantes pour survoler des zones profondes bien défendues.

En revanche, un véhicule hypersonique dispose par nature de ces capacités, qui le démarquent sensiblement des autres systèmes.

Pour préciser son potentiel d'emploi dans le domaine stratégique, nous proposons de distinguer le renseignement statique et le renseignement dynamique, selon le rapport de chacun d'eux avec le temps (durée d'acquisition et d'exploitation, durée de vie de l'information, capacité de rendez-vous, effet de surprise, permanence en vol...).

L'analyse des missions correspondant à cette classification, menée en examinant les capacités offertes par les moyens actuels (drone tactiques, HALE, avions de reconnaissance, satellites) fait apparaître des besoins non couverts pour lesquels un drone hypersonique pourrait constituer un atout significatif.

3. Besoins généraux pour le renseignement stratégique

3.1. Nature de l'information stratégique recherchée

L'intérêt présenté par les grandes vitesses dans le domaine de la reconnaissance stratégique peut être tout naturellement abordé d'une manière globale par l'analyse des échelles de temps mises en jeu, qui peuvent évoluer entre quelques minutes et quelques mois. Cette analyse fait apparaître deux grandes classes d'informations stratégiques, que nous appellerons *statiques* et *dynamiques*.

3.1.1. Renseignement Stratégique Statique

Le recueil du renseignement stratégique statique relève d'une action de fond, qui a pour but d'engager des actions de planification à moyen et long terme. Élément de décision pour les états-majors et les politiques, l'information est généralement mise en forme de manière à présenter une situation (militaire, industrielle, économique), et qui pourra être actualisée périodiquement sous forme synthétique.

Elle permet notamment l'établissement de cartes thématiques:

- réseaux de communication (télécommunications, routes, hydrographie, ponts, voies ferrées, gares)
- énergie (centrales, raffineries, réseaux de distribution)
- sites militaires (aéroports, site radar, site missile, dépôts de carburant ou de munitions)
- sites industriels (usines, centres de recherche)
- modèles de terrain (altimétrie)
- cartes géographiques et économiques (culture, eau, forêt, ville)

Pour présenter une information de haut niveau, souvent issue de la fusion de sources multiples (images multi-bande, multi-résolution, multi-date, écoute électromagnétique, donnée exogène), les temps de traitement sont assez importants. Les évolutions à analyser sont relativement lentes. La durée de pertinence des informations se chiffre au minimum en semaines, et le plus souvent en mois. La mise à jour concerne l'ensemble du territoire, et traite des objets de taille assez importante, pour lesquels des résolutions comprises entre 1 et 30m sont suffisantes.

Les satellites sont bien adaptés pour fournir ce type de renseignements, tant dans le domaine de l'imagerie que pour l'écoute électromagnétique. Toutefois, la persistance de la couverture nuageuse sur certaines zones géographiques, qui peut atteindre 70% en centre Europe, pénalise les systèmes passifs travaillant dans le visible, l'infrarouge proche, ou l'infrarouge thermique.

3.1.2. Renseignement Stratégique Dynamique

Une deuxième classe d'information concerne des évènements beaucoup plus brefs, d'une durée de pertinence de quelques jours à quelques minutes. L'aspect dynamique dépend fortement de la mission.

Recueil de preuves: la mission consiste à obtenir des informations ayant valeur de preuve dans le cadre du respect de traités (non prolifération chimique ou nucléaire par exemple), et fournissant des éléments de négociation auprès des instances internationales. Son succès dépend de la capacité du système à se trouver au rendez-vous d'un évènement qui peut être de courte durée, dont on aurait connaissance par un moyen externe. Il suppose des capacités tous temps, une présence sur site imprévisible, une disponibilité immédiate, et des résolutions au sol mieux que métriques.

Analyse des forces et de leurs mouvements: au niveau stratégique, on s'intéresse à l'activité en profondeur derrière les lignes de front ou de frontière. L'attention se porte sur les axes de communication, qui suppose des capacités de former la trajectoire du véhicule. Une analyse quantitative et qualitative requiert des résolutions comprises entre 30cm et 4m environ. Le suivi des mouvements impose des rafraîchissements fréquents (au moins quotidiens).

Paper presented at the AGARD MSP Symposium on "System Design Considerations for Unmanned Tactical Aircraft (UTA)", held in Athens, Greece, 7-9 October 1997, and published in CP-594.

Préparation d'attaque au sol à grande distance: dans le cadre d'une attaque au sol, l'acquisition d'une image de la cible (ou des zones prévues pour les recalages) dans des conditions proches de celles de l'attaque, favorise grandement la précision de la navigation et du guidage terminal. Les données à recueillir sont peu nombreuses, mais doivent être exploitées sans délai, pour que l'attaque ait lieu avant toute dégradation de l'information. Les contraintes à respecter concernent les senseurs (même nature d'information pour la reconnaissance et l'attaque), la capacité de suivre une trajectoire, la géométrie des prises de vue (latérales ou verticales pour la navigation, frontales pour un recalage terminal).

Surveillance: la mission consiste à détecter les mouvements anormaux aux abords du territoire à défendre, et à écouter fonctionner les différents réseaux de télécommunication. L'intérêt débute en zone frontalière et se prolonge jusqu'au coeur du territoire. Sont principalement concernés la détection de cibles au sol ou aériennes, le départ de missiles balistiques, les communications de commandement, la localisation des radars.

Analyse du réseau de défense pendant l'agression: en période de crise, lorsqu'un avion, un missile ou un drone pénètre sur le territoire adverse, il est pris en charge par les systèmes de défense. L'analyse de leur comportement peut fournir de nombreux éléments concernant les performances de détection (passage de la veille à la poursuite, mise en oeuvre des conduites de tir). Des éléments intimes du système de défense sont alors accessibles pendant de brèves périodes d'alerte, par exemple lors de l' intrusion d'un véhicule rapide équipé de moyens d'écoute.

Ces informations à caractère dynamique peuvent être exploitées immédiatement ou en différé selon le cas, mais elles ont en commun de posséder au moins un temps caractéristique court.

Pour les renseignements de type image, on s'intéresse à des zones géographiques de faibles dimensions pour lesquelles on disposera souvent déjà de cartes renseignées. Les missions seront généralement dédiées à l'analyse d'un site particulier, sur lequel on recherchra une description aussi fine que possible.

4. Potentiel des systèmes d'observation et d'écoute en contexte stratégique

4.1. Systèmes "classiques"

4.1.1. Drones HALE

L'endurance permet une mise à poste de longue durée sur un site à surveiller. Elle est également exploitée pour rallier des zones d'intérêt qui sont très éloignées du point d'origine sans nécessiter un transport.

La haute altitude permet d'observer un domaine au sol de grandes dimensions, et en particulier de traiter simultanément plusieurs cibles éloignées les unes des autres. Elle permet également de minimiser les interférences avec les opérations aériennes qui se déroulent plus bas. Enfin, elle place le véhicule hors de portée des moyens d'interception sol/air classiques. Toutefois, ces véhicules subsoniques qui évoluent à moins de 28000m et qui sont peu manoeuvrants demeurent assez vulnérables face à des missiles air/air tirés depuis un avion d'interception haute altitude.

Malgré les portées très importantes qui peuvent être atteintes, les faibles capacités de pénétration des drones HALE leur réservent donc un emploi stratégique privilégié dans le domaine de l'observation à distance de sécurité:

- détection de missiles balistiques
- surveillance des mouvements des forces aux abords du territoire
- écoute électromagnétique

Ces systèmes ne couvrent pratiquement pas les besoins en imagerie haute-résolution impliqués par le renseignement stratégique dynamique. Ils ne permettent pas davantage l'étude des émissions issues des défenses situées autour d'un objectif profond.

4.1.2. Avion de surveillance subsonique

Les avions de surveillance sont destinés à des missions de même type que les drones HALE en stand-off, en opérant toutefois à altitude beaucoup plus basse. La portée des systèmes d'écoute (horizon radioélectrique) est donc plus réduite. En contrepartie, la grande capacité d'emport de ces avions permet d'analyser simultanément de nombreuses bandes de fréquence, et de traiter à bord les signaux recueillis. Ceux-ci peuvent alors être exploités immédiatement pour orienter la suite des recherches sur un domaine présentant une activité particulièrement intéressante.

4.1.3. Satellites

Les systèmes à base de satellites d'observation sont très bien adaptés pour le recueil du renseignement stratégique "statique". Ils permettent des acquisitions régulières sur toute zone du globe avec des résolutions fines en SAR ou en optique, en s'affranchissant totalement des contraintes liées aux interdictions de survol.

Les meilleures résolutions ne sont toutefois envisageables que dans le domaine optique pour lequel il faut, dans certains cas (notamment en centre Europe), attendre plusieurs semaines avant d'obtenir des conditions de prise de vue satisfaisantes (présence du satellite et ciel suffisamment dégagé). Les zones sur lesquelles il est possible d'obtenir de fréquents rafraîchissements sont encore plus rares.

L'emploi de SAR sur un satellite permet, outre l'aspect tous temps, d'exploiter pleinement le concept d'antenne synthétique grâce aux très grandes vitesses de déplacement (>7500m/s). Néanmoins, la haute altitude tempère cet avantage de vitesse, car elle dégrade la résolution Doppler en réduisant les vitesses de défilement angulaire de la scène. Les grandes distances d'observation (hautes altitudes) imposent en outre des puissances installées importantes (système à imagerie active), pénalisant ensemble la masse, la durée de vie et le coût de lancement.

Enfin, les satellites sont faciles à détecter, et leurs trajectoires obéissent à des lois assez simples de sorte que leur présence est souvent prévisible. Une organisation rigoureuse doit permettre de mener des opérations au sol qui soient discrètes vis à vis de l'observation spatiale.

Les missions impliquant une capacité de rendez-vous et de très hautes résolutions (recueil de preuves, analyse détaillée des cibles), ou une courte période de revisite (mise à jour des mouvements des forces au sol) ne sont pas correctement remplies par ces systèmes.

4.1.4. Avion de reconnaissance supersonique

La présence d'un ou plusieurs pilotes dans l'avion impose des contraintes très lourdes sur le véhicule. Le véhicule doit donc être conçu pour être pratiquement invulnérable, au moins contre des défenses conventionnelles (moyens air/air ou sol/air non nucléaires).

Dans le même esprit, la fiabilité de l'avion doit être excellente pour éviter une panne grave en cours de mission. Ceci impose de nombreuses redondances (notamment concernant la motorisation).

La grande taille de ce type d'avion offre des avantages importants en terme de capacité d'emport et de traitement. Elle permet également la mise en place d'antennes aux extrémités de l'appareil: la grande taille du réseau ainsi constitué est très favorable à la précision de localisation des sources au sol. De même, la taille des optiques permettant d'obtenir les hautes résolutions souhaitées ne pose plus de problème d'intégration dans l'appareil.

Le concept possède potentiellement les qualités requises pour les missions de renseignement en profondeur. L'aspect furtivité en croisière doit être correctement pris en compte si on veut assurer la mission "recueil de preuve" en bénéficiant au mieux de l'effet de surprise. En revanche, l'emploi de systèmes actifs d'imagerie (Laser, SAR) ne pénalisent pas la mission car il ne révèlent la présence du système que pendant l'acquisition des données.

Dans le cas de très grandes vitesses (M=4 à 6), la motorisation constitue également un point délicat à traiter, car elle doit aussi assurer le fonctionnement à basse vitesse (décollage et atterrissage).

Les coûts très élevés constituent le principal obstacle à ce type de programme.

4.1.5. Drone ou avion furtif subsonique

Ces concepts cherchent à exploiter au mieux la furtivité (radar, infrarouge, acoustique) pour pouvoir approcher des objectifs à une distance telle qu'elle permette une acquisition à haute résolution. L'approche à basse altitude permet de tirer profit du fouillis de sol et du relief.

Du point de vue des senseurs, le vol en suivi de terrain pourrait permettre d'approcher les capacités tout-temps sans recourir au radar. L'essentiel du couvert nuageux se trouve au dessus de la ligne de visée, de sorte que l'utilisation de senseurs visibles ou infrarouges semble moins limitée par l'absorption atmosphérique que depuis la haute altitude.

Cependant, plusieurs arguments peuvent être opposés à ce concept.

a - Il ne semble pas possible d'obtenir une pénétration réellement profonde sans une phase initiale à une altitude plus élevée qui permet de réduire les consommations de carburant et d'obtenir la portée requise. L'avion se trouve alors vulnérable pendant une durée assez longue, et l'interception dans cette phase pourrait demeurer assez aisée, d'autant que la recherche de la furtivité n'est pas très favorable aux performances aérodynamiques, en particulier en ce qui concerne la manoeuvrabilité.

b- Malgré une excellente furtivité et un vol en suivi de terrain, les seuils de détection des systèmes de défense ne devraient pas permettre le survol direct d'une cible défendue. Les prises de vues seront donc nécessairement rasantes si on ne tolère pas une excursion importante en altitude. On voit mal comment une telle image pourrait correctement décrire l'activité d'un site industriel, compte tenu des effets de masquage par les arbres, le relief, ou les bâtiments entre eux.

c- L'intégration des senseurs doit faire l'objet d'un soin extrême pour maintenir la SER à son plus faible niveau dans les directions sensibles. Les niveaux de SER déterminent directement les performances du concept et peuvent constituer une source de risque technologique.

Si l'utilisation d'un drone ou d'un avion furtif pour le recueil d'images à haute résolution présente un certain nombre d'avantages liés essentiellement à la possibilité d'approcher un objectif d'assez près, on constate qu'une analyse plus détaillée des missions à réaliser fait surgir de nombreuses limitations d'emploi.

4.2. Missions de base pour les drones hypersoniques

Les systèmes que nous venons d'évoquer ne permettent de répondre que partiellement aux besoins exprimés dans le domaine du renseignement stratégique. Pour la plupart des mission, les caractéristiques spécifiques des drones hypersoniques en font au minimum une alternative avantageuse:

- coût faible par rapport à un programme de type avion
- invulnérabilité face à pratiquement tout système d'arme
- non compromission garantie par l'absence de pilote, l'invulnérabilité, et éventuellement une désintégration haute altitude en cas de panne
- capacité de rendez-vous en temps et en espace
- un délai d'arrivée sur site très réduit
- possibilité de survol direct pour obtenir des vues plongeantes successives permettant une reconstruction 3D

Recueil de preuve:

Cette mission consiste généralement à obtenir une prise de vue contenant l'information recherchée. Le drone hypersonique n'est pas contraint à des visées rasantes. L'aptitude à l'effet de surprise permet d'analyser l'activité en dehors des horaires de passage des satellites, et avec une meilleure résolution. Enfin, on peut envisager que le délai entre la connaissance d'une activité en cours sur un site éloigné de 1000 km et l'acquisition de la preuve de cette activité soit inférieur à 30 minutes.

Préparation d'attaque au sol:

La période de rafraîchissement du renseignement "statique" est assez importante (souvent plus de 6 mois). Pour la navigation autonome par imagerie radar d'un missile air/sol à très longue portée ou d'un missile de croisière subsonique en suivi de terrain, la recherche d'une bonne précision finale impose des recalages fréquents qui nuisent à la furtivité ou introduisent des contraintes de trajectoire (survol des régions pauvres en amers). Une imagerie réalisée juste avant la mission (quelques heures ou quelques minutes) favorise grandement la qualité des correlations calculées pendant l'attaque, et accroissent la précision de la navigation. De même, lors du recalage terminal, il devient possible de désigner avec précision la cible dans une image presque identique à celle qui sera vue lors de l'attaque.

Surveillance et suivi des mouvements de force:
A la différence de la surveillance tactique qui implique la permanence sur zone, la surveillance stratégique concerne un niveau de décision plus global. Dans ce contexte, les drones hypersoniques permettent d'envisager un bilan de l'état d'activité de très nombreux sites simultanément. A titre d'exemple, un petit nombre de missions pourrait suffire à imager en quelques heures tous les régiments de chars. Cette mission requiert des capacités de stockage plus étendues que pour les autres missions.

Ecoute sur trajectoire pénétrante:
Cette mission s'oriente principalement vers l'écoute des systèmes de défense situés en profondeur dans le territoire. Leurs émissions ne peuvent en effet pas être captées depuis les frontières car elles se situent au-delà de l'horizon radioélectrique. Par ailleurs, les radars de poursuite fonctionnent essentiellement lors des intrusions, et pourraient rester assez discrets le reste du temps. Ainsi, les drones rapides se prêtent assez bien à des missions de survol des zones présumées être des sites radar, afin d'en confirmer la nature et d'identifier quelques caractéristiques (bande, mode, puissance...). Inversement, on peut également exploiter ces drones pour fournir une localisation approximative de sources radar nouvelles ou qui auraient échappé aux photo-interprètes dans les images satellitaires.

Aucune de ces missions n'imposent fondamentalement de pouvoir modifier la trajectoire en fonction des données recueillies. Elles s'accommodent bien de paramètres programmés, de l'absence d'un pilote, de capacités de traitement modestes, et de moyens de communication très réduits, voire inexistants.

5. Charges utiles pour la reconnaissance stratégique

Dans cette partie, nous analyserons les moyens d'imagerie passive (visible, IR) et active (SAR), puis l'apport de charges de type SIGINT pour les missions opérationnelles envisagées

5.1 Imagerie SAR

5.1.1 Recherche de performances tous temps

Les ondes radar ont la propriété d'être faiblement atténuées par l'atmosphère, ce qui permet d'envisager des performances tous temps. Ce point est particulièrement important en centre Europe, où le couvert nuageux limite très fortement l'utilisation d'imageurs dans le visible et l'infrarouge. La figure 1 donne des valeurs typiques d'atténuations dues à l'atmosphère en présence de précipitations, depuis les fréquences radar jusqu'au domaine visible (ref [1] page 8)

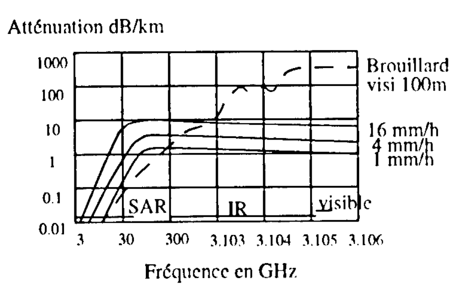


Fig 1: atténuation atmosphérique

L'atténuation augmente avec la fréquence des ondes radar, mais reste négligeable en atmosphère claire. Sur un trajet aller-retour oblique plongeant depuis une altitude de 30km, elle est en effet inférieure à 2 dB pour toute la gamme de fréquence de 1 à 35 GHz.[2]

L'intérêt du radar, déjà évident en présence de pluie, devient énorme en présence de nuages. Sur un parcours aller-retour traversant un nuage dense pendant 1km, on doit comparer 0.2dB au dessous de 30GHz avec plus de 200dB en IR proche et dans le visible.

5.1.2 Principe de l'antenne synthétique

L'ouverture d'un faisceau radar (qui détermine la résolution qui pourra être obtenue) est inversement proportionnelle à la taille de l'antenne. Pour des applications d'imagerie, la recherche de hautes résolutions passe par des antennes dont la taille excède largement celle des engins qui les emportent.

Le principe de l'antenne synthétique consiste à reconstituer par un traitement cohérent une antenne virtuelle dont la longueur est égale à la distance parcourue par le porteur pendant le temps d'illumination. Dans ces conditions, on perçoit nettement l'intérêt que peut offrir un drone évoluant à des vitesses élevées. En effet, à Mach 5, une durée d'intégration de 1.5s nous ramène, selon le calcul précédent, à une antenne équivalente de 2250m.

Les hautes vitesses constituent donc un facteur qui est favorable à l'obtention de hautes résolutions. Toutes choses égales par ailleurs, la résolution s'améliore avec le rapport entre la vitesse du porteur et l'altitude (défilement du sol qui détermine la résolution Doppler). Le tableau I donne des valeurs caractéristiques de ces paramètres, montrant potentiellement un facteur supérieur à 2 en faveur des drones hypersoniques par rapport aux satellites.

Tableau I	Z (km)	V (m/s)	V/Z
drone basse altitude	1	80	80
drone Hypersonique	30	1350	45
Satellites	400	7500	18.8
drone HALE	27	120	4.5

Sur un drone HALE, la recherche d'un renseignement en profondeur, derrière la ligne frontière, conduit ces derniers à opérer à grande distance, sous des incidences assez rasantes. Les phénomènes d'absorption limitent l'utilisation des radars à des longueurs d'onde assez basses. De plus, le masquage du terrain par le relief rend certains sites inaccessibles à l'observation.

A l'inverse, les drones hypersoniques peuvent approcher leurs objectifs pour se placer dans les conditions de prise de vue les plus favorables. Les phénomènes d'absorption étant réduits, on pourra utiliser des longueurs d'ondes plus petites, ce qui est à nouveau favorable à la résolution, et diminue ensemble les tailles d'antennes et les puissances installées.

5.2 Équipement ELINT/COMINT

On cherche maintenant à tirer profit de la menace engendrée par la pénétration haute altitude d'un véhicule à grande vitesse. Un tel comportement est supposé mettre en alerte l'ensemble du réseau de défense et, en particulier, les radars de détection, de poursuite et de conduite de tir. Le dispositif embarqué doit remplir les deux fonctions suivantes:

a - localiser les sources non répertoriées:
La mission consiste en un survol d'une région supposée contenir des sites radar en raison de la présence de cibles à haute valeur. Il peut s'agir également de missions à caractère systématique, prenant la forme d'un quadrillage du territoire. Quelques missions effectuées selon des hippodromes permettent de traiter un domaine de 1000 km x 1000 km en survolant chaque point avec un déport latéral maximal modéré. Le système d'écoute doit couvrir le plus grand domaine angulaire possible. Les précisions qui peuvent être atteintes sont directement liées à la taille du porteur, qui détermine les distances maximales entre antennes. Par ailleurs, si on dispose à bord des traitements pour la détection/localisation et de l'imagerie SAR, on peut envisager d'intéressantes synergies.

b - analyser des sources de positions connues:
L'analyse des modes de fonctionnement d'un radar de position connue suppose une capacité à orienter l'écoute sur un secteur angulaire particulier, variable pendant le survol. Les traitements à mettre en place passent par une analyse détaillée des systèmes à écouter. Mieux leurs caractéristiques seront connues à l'avance, plus les informations recueillies seront détaillées:

- fréquence en mode surveillance, cadence des impulsions, puissance, polarisation
- apparition d'un mode de poursuite: distance, recherche de la bande, agilité, puissance
- éventuellement, engagement par une conduite de tir

Une trajectoire bien choisie peut permettre de survoler plusieurs sites en une seule mission.

Le traitement de ces informations permet d'accéder à des informations de haut niveau. Les instants auxquels se produisent les changements de modes renseignent sur les performances du réseau (distance de détection, temps de réaction...) ainsi que sur sa philosophie d'emploi.

5.3 Imagerie IR passive

5.3.1 Généralités

L'imagerie passive dans l'IR exploite les émissions spontanées des constituants de la scène, qui dépendent des matériaux qui les constituent et de leur température. Le principe fonctionne donc de jour et de nuit, avec toutefois des images différentes (fréquentes inversions de contraste thermique), et une très forte influence des conditions atmosphériques.

Les performances des systèmes d'imagerie IR sont principalement caractérisées par leur résolution spatiale (de même qu'en imagerie visible), et par leur résolution thermique. En effet, les images recherchées ressemblent beaucoup à une carte de température, de sorte que les contours physiques des objets n'apparaissent que s'ils témoignent d'un contraste thermique par rapport au fond de scène.

<u>La résolution spatiale</u> dépend de plusieurs facteurs:

a - La turbulence atmosphérique provoque une déviation des rayons lumineux (gradients d'indice de réfraction), qui se traduit par une agitation des images dans le plan focal. Pour des temps de pose courts, elle peut induire des déformations locales de l'image, de sorte que la conformité géométrique peut être dégradée. Inversement, pour des temps de pose longs, ces agitations locales sont moyennées: la conformité géométrique est restaurée, mais le lissage temporel introduit du flou sur les petits objets. Cette turbulence à long terme dépend des caractéristiques de l'atmosphère et peut facilement être modélisée sous la forme d'une fonction de transfert.

b - La diffraction de l'onde incidente sur la pupille crée dans le plan image une tache dont la taille correspond, dans la scène, à la taille minimale des objets qui peuvent être discriminés (indépendamment des autres phénomènes perturbateurs). Cette taille (rayon caractéristique rc), correspondant à une fréquence spatiale de coupure, est donnée par:

$$rc = \frac{\lambda . L}{D}$$

où: l longueur d'onde
L distance de la cible
D diamètre de la pupille

c - L'échantillonnage spatial par la barrette ou la matrice de détecteurs située au plan focal image introduit une perte d'information sur le signal initial: la valeur affectée à un pixel correspond à une moyenne des flux reçus sur la surface du détecteur. La recherche de hautes résolutions passe par l'élaboration de détecteurs de petite taille, et l'emploi de grande focales.

Ces facteurs de dégradation s'expriment sous la forme d'une fonction de transfert appelée FTM (fonction de transfert de modulation), obtenue par le produit des FTM de chaque phénomène, et caractérise l'atténuation que subit le signal pour une échelle spatiale donnée (souvent représentée sous forme fréquentielle).

<u>La résolution thermique</u> dépend du rapport signal/bruit du système: on cherche à maximiser le nombre de photons provenant de la scène, en sorte de créer un nombre de charge grand devant le bruit propre des détecteurs, en demeurant cependant au dessous du seuil de saturation. Le nombre de photons est favorisé par une grande pupille, une scène chaude, une faible atténuation atmosphérique, et un long temps d'intégration. Ce dernier doit toutefois être choisi en sorte d'éviter les phénomènes de bougé, qui dépendent de la vitesse du porteur.

Pour une température de scène et des caractéristiques données pour l'atmosphère et le senseur, on peut calculer le NETD (Noise Equivalent Temperature Difference) pour une bande de fréquences donnée.

Pour représenter la détectabilité des cibles, on utilise le MRTD (différence de température minimale résolue) qui, pour une dimension de cible donnée, détermine l'écart de température qu'elle doit présenter par rapport à son environnement pour être détectée.

Sur la base de ces considérations, on constate rapidement que les limitations de performances ont des origines très différentes en bande II et en bande III.

5.3.2 Cas de la bande III (λ = 8-12μ)

Dans cette partie du spectre, on travaille avec des longueurs d'onde assez grandes, pour lesquelles l'effet de la diffraction est très pénalisant. La figure 2 montre les FTM obtenues pour une optique de 1m de focale et une pupille de 200mm de diamètre, en prenant en compte l'échantillonnage et la diffraction.

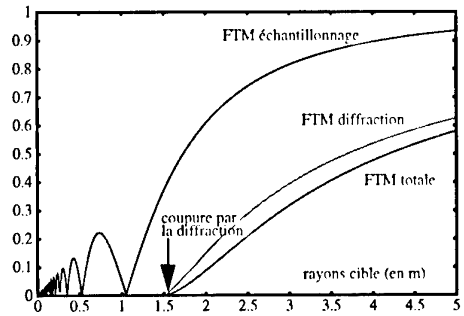


Fig 2: FTM bande III - f = 1m

Pour cette pupille, la taille de la tache de diffraction correspond à une cible de 1.5m de rayon. Une résolution inferieure au mètre impose des diamètres de pupilles de l'ordre de 1m, ce qui pose de délicats problèmes d'intégration.

En contrepartie, la scène fournit en bande III une grande quantité de photons, qui permettent de maximiser le rapport signal/bruit des détecteurs avec des temps de pose très courts: les temps d'intégration sont assez faibles pour éviter les effets de bougé sans qu'il soit nécessaire de compenser les mouvements

5.3.3 Cas de la bande II (3 à 5 μ)

Dans cette bande, on travaille avec des longueurs d'onde plus courtes, pour lesquelles les effets de la diffraction sont moins pénalisants. Toutefois, avec une pupille de 200mm, la taille critique d'une cible à 30km est de l'ordre de 1.20m.

Par ailleurs, la bande II fournit moins de photons que la bande III, de sorte que les temps d'intégration doivent être sensiblement accrus si on veut conserver une résolution thermique satisfaisante. À grande vitesse, il peut devenir nécessaire de compenser les effets de bougé pendant le temps d'intégration.

5.3.4 Optique visible et proche IR

En bande visible, on exploite la réflexion de la lumière solaire par la scène. La température de scène n'intervient plus dans les bilans de liaison, et c'est l'éclairement qui joue le rôle dominant. Les différentes sources de FTM existent toujours, mais l'utilisation de petites longueurs d'onde réduit très sensiblement les limitations dues à la diffraction.

Un système optique dans le visible devrait répondre au besoin de résolution avec de petites pupilles, mais pas sous l'aspect tous temps, ni la nuit.

5.3.5 Bilan concernant l'imagerie passive

La Bande III semble exclue pour obtenir une très haute résolution à haute altitude sur un véhicule petit. L'IR passif prend tout son intérêt en bande II sur des véhicules capables de recevoir des optiques d'au moins 400mm de diamètre.
La bande visible est utilisable facilement mais se limite aux cas diurnes de ciels dégagés.

Des compléments d'étude demeurent nécessaires pour préciser:

- l'influence des effets aéro-optiques
- les méthodes de balayage (miroirs mobiles, cadence...)
- les besoins de refroidissement pour l'IR

6. Mise en oeuvre opérationnelle

6.1 Modes de lancement

La propulsion par statoréacteur, parfaitement adaptée aux profils de mission comportant une croisière à haut Mach, impose des contraintes dans les phases basses vitesse, car la poussée que peut délivrer le moteur n'est significative qu'à partir d'une vitesse assez élevée (Mach > 2^+). Pour atteindre ces conditions de fonctionnement du statoréacteur, on doit mettre en place un moyen d'accélération initial.

La solution d'un accélérateur intégré permet d'exploiter pleinement le volume de la chambre de combustion en la remplissant de poudre. La structure de la chambre doit alors être dimensionnée pour résister aux fortes pressions qui apparaissent dans cette phase. Par ailleurs, les opercules d'entrée d'air doivent être éjectés en fin d'accélération.

Un accélérateur largable permet de s'affranchir de ces deux derniers points (seule la structure du booster est soumise aux fortes pressions), mais le volume alloué à la poudre est plus réduit.

Ces deux concepts sont applicables lorsque l'incrément de vitesse à communiquer n'est pas trop grand (choix des conditions de largage).

Dans le cas d'un tir depuis le sol, la quantité de poudre nécessaire n'est plus compatible avec le volume interne de la chambre, et on utilise un booster externe.

Une alternative aux accélérateurs à poudre peut être offerte par l'emploi d'un mode fusée à effet éjecteur, notamment dans le cas d'un véhicule de grande taille intégrant le réservoir supplémentaire nécessaire. Le reconditionnement après retour de mission pourrait être grandement simplifié par rapport à une solution à accélérateur intégré.

6.2 Récupération de l'engin

La récupération du drone est une phase indispensable pour limiter les coûts.

Classiquement, les senseurs constituent un poste très important, de même que les équipements de navigation. Pour un drone évoluant à très grande vitesse, la structure du véhicule représente également un coût sensible, notamment si des matériaux absorbants radar haute température devaient être mis en place.

La longévité de la chambre de combustion (en nombre de mission réalisable) est plus difficile à estimer, et dépend fortement des technologies mises en oeuvre (puits de chaleur, chambre refroidies...), elles-mêmes liées aux impératifs de trajectoires (flux, durées) et aux dimensions du véhicule.

Il en va de même pour les éléments externes comme les entrées d'air ou les gouvernes, pour lesquelles on conçoit que la récupération pourrait être à l'origine d'impacts locaux sur la structure.

Il est donc certain que l'emploi d'un drone hypersonique, dédié au recueil de renseignements ponctuels à haute valeur, nécessitera d'une part de le récupérer, et d'autre part d'effectuer un certain nombre de contrôles entre deux missions successives.

Plusieurs modes de récupération peuvent être envisagés:

a - retour autonome sur une piste

Pour les véhicules capables d'un décollage autonome, le retour sur piste est une solution naturelle. Cette solution laisse toutefois posés les problèmes suivants:

- contraintes sur la trajectoire, la portée, les manoeuvres finales
- contrôle de l'approche à basse vitesse (efficacité des gouvernes, stabilité, degré d'automatisation...), puis pendant le ralentissement au sol (impact, glissement ou roulement)
- intégration dans le trafic aérien, notamment en vol supersonique

Cette solution serait particulièrement bien adaptée pour un véhicule disposant d'un très grand rayon d'action, peu contraint par la localisation des pistes utilisables.

En revanche, un drone "minimal" ne devrait pas disposer de toutes ces qualités de vol.

b - récupération par parachute

Ce mode de récupération permet a priori de tirer un meilleur parti de la portée du véhicule, car il peut être envisagé dès le retour en zone amie, en s'affranchissant des contraintes sur la localisation des pistes d'atterrissage et les trajectoires d'approche.

Le dimensionnement de la chaîne parachutale et d'un éventuel dispositif d'amortissement sur coussin gonflable est toujours possible, mais il pénalise directement le volume alloué au carburant ou aux équipements.

L'utilisation d'un hélicoptère pour recueillir en vol le véhicule sous son parachute semble un mode de récupération plus avantageux:

- élimination des risques associés à l'impact (senseurs préservés, même peu durcis)
- suppression du problème d'intégration de dispositifs d'amortissement
- le choix du taux de chute, qui ne dépend que des performances de l'hélicoptère et du savoir faire des pilotes, permet de réduire la taille du parachute
- guidage/pilotage rudimentaire en phase terminale (vol rectiligne)
- choix de la zone au sol sans importance (récupération aérienne)
- le recueil en mer ne change rien au procédé

Le système de récupération américain MARS (Mid Air Retrieval System) fonctionnait sur ce principe pendant la guerre du Viêt-nam pour des drones de grande taille largués par un gros porteur DC-130 HERCULES.

La possibilité de prolonger aussi loin que possible le vol aux basses vitesses permet de réduire les spécifications concernant l'ouverture du parachute de freinage. Il est dont utile, même si on ne cherche pas à poser le véhicule sur une piste, d'en évaluer le comportement dans ce domaine de vol inhabituel.

6.3 Liaison avec le sol

Les échanges d'information entre un drone et une station de contrôle nécéssitent la mise en place d'une liaison de données dont les caractéristiques diffèrent fortement selon le sens du transfert. La station transmet vers l'engin les données concernant la trajectoire et la gestion des modes des senseurs. Ce mode de contrôle est indispensable pour des missions de longue durée (comme la surveillance), notamment si elles doivent pouvoir être reconfigurées. Il s'agit généralement d'une liaison à faible débit.

Inversement, le drone transmet en retour les données issues des senseurs, qui peuvent conduire à des débits très importants, et qui doivent être protégés contre le brouillage (compression des données, étalement du spectre de transmission, antennes directionnelles). Dans le cas de drones réalisant des images en continu, la transmission est une nécessité, car le stockage serait impossible.

Le vol à haute altitude est favorable à une bonne transmission à grande distance, en raison des faibles atténuation atmosphériques. Il est alors possible d'utiliser des fréquences élevées, autorisant l'emploi d'antennes de petite taille. Toutefois, le bénéfice de cette bonne transmission n'est exploité que si la station de réception se trouve également à haute altitude (avion relais, satellite). En revanche, un transfert direct vers le sol ne semble pas possible à très longue portée car les signaux doivent traverser des couches basses de l'atmosphère: ils sont plus fortement atténués, et peuvent être brouillés par un émetteur situé entre le drone et la station sol.

De plus, même dans le cas favorable d'une station aéroportée à 12000m d'altitude (cas d'un gros porteur qui pourrait également constituer la plate-forme de lancement du drone), les portées radioélectriques avec un véhicule évoluant à 30000m sont de l'ordre de 1100km, ce qui peut constituer une limitation d'emploi lorsque de très grandes distances doivent être parcourues. Le transfert par satellite relais s'impose alors, mais il introduit de fortes contraintes géométriques pour assurer le pointage des antennes.

La mise en place d'une liaison de données pose donc un problème assez complexe, couplant très fortement le véhicule (masse, aérodynamique, pilotage) et son concept d'emploi.

6.4 Contraintes sur les trajectoires

Les contraintes opérationnelles imposent généralement une trajectoire complexe, avec au minimum la contrainte d'une récupération en zone amie.

Les grandes vitesses de croisière imposent des rayons de courbures importants, et guident fortement le tracé du profil de mission. Si on fait l'hypothèse simplificatrice selon laquelle un virage sous facteur de charge latéral k accroît la consommation d'un facteur sqrt $(1 + k^2)$, on constate par exemple qu'un demi tour à Mach 5 sous 1g de facteur latéral (rayon de courbure de 230 km) accroît de 40% la consommation, pendant les 480 secondes de la manoeuvre, c'est à dire sur 720 km de vol.

Il est donc clair que le rayon d'action est nettement inférieur à la moitié de la portée sur trajectoire rectiligne, et qu'il existe une manoeuvre de demi-tour optimale maximisant la pénétration. Par ailleurs, l'intérêt d'utiliser des trajectoires traversantes en dissociant lancement et récupération est d'autant plus grand que la vitesse est élevée.

7. Conclusion

Dans le domaine des résolutions comprises entre 1m et 30m, les drones actuels ou en projet et les satellites constituent des systèmes complémentaires, pour des missions permanentes de surveillance en zone proche des frontières (menace rapidement variable avec effet à court terme), et l'observation en profondeur de menaces à moyen et long terme (activité de sites, aménagement d'infrastructures).

Toutefois, aucun de ces systèmes ne permet actuellement de recueillir avec de courts temps de réponse des renseignements de type image à des résolutions sub-métriques, ou de type électromagnétique en zone profonde. Par ailleurs, l'écoute des réactions des systèmes de défense lors d'une intrusion ne pourraient être envisagée, par principe, que par un véhicule disposant de fortes capacités de pénétration et d'un long rayon d'action.

Ces missions, qui ne peuvent pas être correctement accomplies aujourd'hui, pourraient être couvertes à coût modéré par un drone hypersonique.

Un radar à synthèse d'ouverture devrait constituer l'équipement de base pour la reconnaissance tous temps. L'emploi alternatif (équipement modulaire) ou bimode (synergie), de l'imagerie passive est également possible, mais son potentiel est limité notamment par le calibre du véhicule, qui fixe la taille maximale des pupilles qui peuvent être intégrées.

Il est vraisemblable qu'un véhicule de taille modérée (6 à 8m), employé sous avion d'arme ou depuis un gros porteur, pourrait offrir, pour le renseignement stratégique, un excellent compromis entre l'adaptation aux besoins opérationnels et les coûts de développements.

Références bibliographiques

[1] S.A. Hovanessian - Introduction to sensor systems - Artech House 1988

[2] Donald R. Wehner - High Resolution Radar - Artech House

Operational Concepts for Uninhabited Tactical Aircraft

Dwain A. Deets and Dana Purifoy
NASA Dryden Flight Research Center
Edwards, California 93523
U.S.A.

1. ABSTRACT
This paper describes experiences with five remotely piloted flight research vehicle projects in the developmental flight test phase. These projects include the Pathfinder, Perseus B, Altus, and X-36 aircraft and the Highly Maneuverable Aircraft Technology (HiMAT). Each of these flight projects was flown at the NASA Dryden Flight Research Center. With the exception of the HiMAT, these projects are a part of the Flight Research Base Research and Technology (R&T) Program of the NASA Aeronautics and Space Transportation Technology Enterprise. Particularly with respect to operational interfaces between the ground-based pilot or operator, this paper draws from those experiences, then provides some rationale for extending the lessons learned during developmental flight research to the possible situations involved in the developmental flights proceeding deployed uninhabited tactical aircraft (UTA) operations. Two types of UTA control approaches are considered: autonomous and remotely piloted. In each of these cases, some level of human operator or pilot control blending is recommended. Additionally, "best practices" acquired over years of piloted aircraft experience are drawn from and presented as they apply to operational UTA.

2. INTRODUCTION
This paper describes experiences with five NASA-sponsored uninhabited flight research vehicle projects in the developmental flight test phase. The intent is to draw some insights from this set of experiences that might apply to operational concepts for uninhabited tactical aircraft (UTA). Lessons learned from these experiences may have more applicability to the developmental flight test phase of operational vehicles, but such application requires special attention as new air combat tactics involving UTA emerge. Following the descriptions and characterization of the five projects, some suggestions are made for future operational systems, and a set of "best practices" is offered.

3. GENERIC CATEGORIZATION OF REMOTELY-PILOTED VEHICLES
As a start, an attempt is made to set out useful generic categorizations that span the five flight projects. The first categorization is more of a reminder that the project experiences come from the developmental testing phase. Having development testing and operational deployment experiences would have been good, but only development testing was within scope of these flight research projects.

One important variation between projects pertains to the amount and type of human interaction involved in controlling the aircraft. High bandwidth of interaction up to rigid-body frequencies is characterized as "remotely piloted." Low bandwidth of control, to the point of infrequent human interactions, tends toward "autonomous." Note that reaching 100-percent autonomy was not an objective of these five projects.

Other generic categories involve the amount of system redundancy and the action taken to constrain public exposure in the event of catastrophic failure. All five vehicles are recovered through conventional horizontal landing. The launch methods are either horizontal takeoff or air launched. A characteristic of any of these developmental testing projects is that the vehicles must stay within the test range. For piloted aircraft, the requirement to stay within the test range can be met almost by assumption. For an uninhabited vehicle, however, assurance of positive control with respect to the test range boundaries, even after major system failures, becomes a dominant requirement. Thus, one of the key descriptors in characterizing the various flight vehicles is by their approach to either backup recovery or flight termination. Related is their approach to systems redundancy.

4. DEVELOPMENT TESTING EXPERIENCE
Figure 1 lists the projects in order of increasing airspeed. The Pathfinder, Perseus B, Altus, and X-36 vehicles are part of the NASA Flight Research Base Research and Technology (R&T) Program. These vehicles are currently flying or have been flown at Dryden Flight Research Center, Edwards, California.

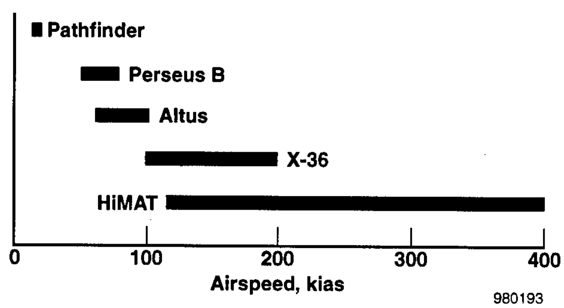


Figure 1. Vehicle projects in order of increasing airspeed.

The first three are members of the Environmental Research Aircraft and Sensor Technology (ERAST) set of projects. Pathfinder is a solar-powered very high-flying airplane. The Perseus B and Altus are high-altitude, slow-flying, consumable fuel aircraft. These aircraft are designed for uninhabited aircraft operational applications. The X-36 and HiMAT (Highly Maneuverable Aircraft Technology) differ because they are subscale, remotely piloted vehicles which are representative of hypothetical, full-scaled, inhabited vehicles. These subscale vehicle designs are probably different than they would have

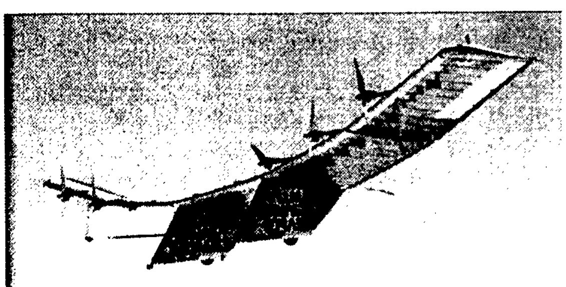
Paper presented at the AGARD MSP Symposium on "System Design Considerations for Unmanned Tactical Aircraft (UTA)", held in Athens, Greece, 7-9 October 1997, and published in CP-594.

been if there were no intent to have them up-scaleable to piloted versions. With one exception these five vehicles are currently being flown. The last flight of the HiMAT occurred nearly 2 decades ago; therefore, those flights used technology that is antiquated by today's standards. However, important lessons involving vehicles with supersonic capabilities were learned. Remembering such lessons would prove helpful at this point. The HiMAT test results and a program assessment overview are provided in reference 1.

4.1 Pathfinder

The solar-powered Pathfinder was designed, built, and operated by AeroVironment, Incorporated, Monrovia, California. It takes off horizontally and flies at very low airspeed (16.6 kias) throughout its mission. Pathfinder has a wingspan of 100 ft, has wing chord of 8 ft, and weighs 570 lb. The flight control systems have triplex redundancy for the sensors and duplex computers. Emergency positive recovery is by way of a off-center drag chute which initiates a helical decent. This flight program is in the developmental flight test phase. Operator interface is by way of a joystick through an automatic pilot.

Figure 2 shows the Pathfinder. Flights under NASA sponsorship occurred from 1995 to 1997. The most notable accomplishment is the setting of the World Altitude Record for propeller-driven aircraft of 71,500 ft on July 7,1997. Further information is available in reference 2.



EC95 43261-8

Figure 2. Pathfinder solar-powered aircraft.

4.2 Perseus B

The Perseus B was designed, built, and operated by Aurora Flight Sciences Corporation, Manassas, Virginia (figure 3). This pusher-prop, high-altitude, remotely piloted aircraft takes off and lands horizontally. The Perseus B is 26.2 ft long, has a 58.6-ft wingspan, and weighs 2700 lb. Its maximum airspeed is 80 knots, and the flight control system is simplex. Emergency positive recovery makes use of a termination chute.

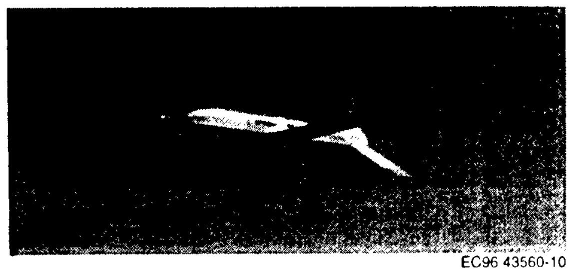
EC96 43439-5

Figure 3. Perseus B in flight.

Flight activity was from 1994 to 1996, with a premature ending to the flight series because of a mishap. Lessons learned from that mishap are presented in reference 3. Completion of the envelope expansion is planned for 1998.

4.3 Altus

The Altus was designed, built, and operated by General Atomics Aeronautical Systems, Incorporated, San Diego, California (figure 4). The Altus I is based on Predator and uses a single turbocharger; whereas, the Altus II uses a dual turbocharger. The Altus is 21.8 ft long, has a 56.3-ft wingspan, and weighs 1632 lb. Its maximum airspeed is 100 knots, and systems redundancy is duplex. Backup recovery is through a Global Positioning System (GPS) way-point loiter. A termination chute deploys if the way-point loiter does not work. Operator interface is through a head-up display (HUD), with forward-looking camera. Control inputs are through stick and rudder pedals.



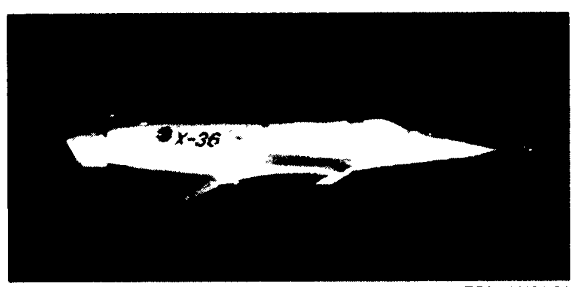
EC96 43560-10

Figure 4. Altus in flight.

Flight testing began in 1996 and continued into 1998. Achieving a maximum altitude of 65,000 ft is planned for later in 1998.

4.4 X-36 Aircraft

Figure 5 shows the X-36 aircraft. This remotely piloted vehicle was designed, built, and operated by the Boeing Phantom Works, St. Louis, Missouri. This airplane is powered by a Williams Research F112 turbojet. The NASA Ames Research Center, Mountain View, California, provided management and strong technical contributions, and NASA Dryden provided flight facilities and operational support.



EC97 44121-24

Figure 5. X-36 in flight.

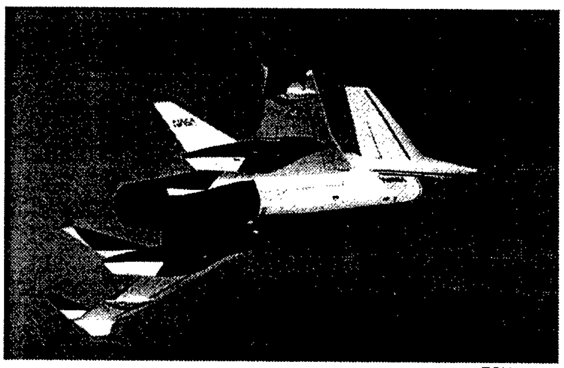
The X-36 is 18 ft long, has a 10-ft wingspan, and weighs 1270 lb. This vehicle takes off and lands horizontally, has flown to a airspeed of 200 knots, has a simplex flight control system, and is equipped with a parachute emergency recovery system. Pilot interface consists of proportional commands to

the flight control system through stick and rudder pedals. A very advanced HUD is used with additional features to make piloting from a ground-based cockpit an effective control mechanism.

This aircraft is in the developmental flight test phase. Flights began in the spring of 1997 and ended before the end of that year. Thirty-one flights have occurred, and no significant problems were encountered. All program objectives were met or exceeded. Further information is available in references 2 and 4.

4.5 HiMAT

Figure 6 shows the HiMAT. This remotely piloted vehicle differs from the other aircraft described in this paper because it was air launched from a B-52 aircraft. However, it landed horizontally in a manner similar to the Pathfinder, Perseus B, Altus, and X-36 aircraft. This aircraft was designed, built, and operated by the North American Aviation Division of Rockwell, Incorporated, El Segundo, California. The flight control system used a ground-based computer interlinked with the aircraft through an uplink and downlink telemetry system. An onboard backup flight control system had duplex redundancy. The maximum airspeed attained was 400 knots. The HiMAT is 23.5 ft long, has a 15.6-ft wingspan, and weighs 3428 lb.



ECN 14273

Figure 6. HiMAT remotely piloted aircraft in flight.

From 1979 to 1982, 26 flights were accomplished. The HiMAT program was completed without any loss of vehicles.

The pilot's interface used proportional stick and rudder pedals for control, with inputs commanding the computer in the primary flight control system. Pilot displays were quite crude. Conventional instrument panel gauges were used and a forward-looking camera served as the source for a cathode-ray tube display. Neither a HUD nor an imbedded symbology on the cathode-ray tube display were used. Further information is available in references 1 and 5.

5. LESSONS LEARNED

Because experiences described here were gained with developmental aircraft, suggestions regarding future UTA systems are being limited to developmental aircraft. These suggestions are grouped into matters pertaining to control approach and matters affecting vehicle design tradeoffs.

5.1 Vehicle Control Approach

On one extreme, vehicle control approach can involve a human operator (pilot) tightly coupled into the control loop. At the other extreme, the vehicle can be completely separate from human interaction (autonomous control). For operationally deployed vehicle systems, the design might draw from the full range of possibilities in vehicle control approach. For developmental vehicle systems, some level of human interaction is recommended, even for the autonomous systems. Some considerations for this range of approaches are given in the Remotely Piloted Control and Autonomous Control subsections.

5.1.1 Remotely Piloted Control

Uninhabited vehicles controlled by remote pilots depend on the pilots being well informed on the complete situation pertaining to the vehicle and mission. In a ground-based remote cockpit, the primary sources of information for the operator or pilot are presented in visual displays or through audio means. The following subsections on visual cues and audio cues address these forms of information transfer.

Visual Cues

Cockpit design is critical, particularly with respect to visual displays. Situational awareness should be as complete as with an inhabited aircraft. This awareness should be maintained even with the absence of motion cues. As a result, extra care should be taken to supplement the standard displays with additional cues that can provide the missing information.

Audio Cues

Audio cues from an onboard microphone can provide important additional information. For the X-36 aircraft, such a cue was provided to the remote pilot. Cues allowed identification of some anomalous engine operations early in the X-36 project. This timely identification prevented difficulties which could have reasonably been expected to occur if corrective action not been taken.

5.1.2 Autonomous Control

Uninhabited vehicles designed for autonomous control should provide some means of oversite by a human operator and limited interaction. During developmental testing, an increased capability for human interaction is usually beneficial. Two desirable attributes of the system design include blending of human interaction and graceful assumption of control by the human.

Provide for Limited Human Blending

In nearly all cases, the ability to blend human control with automation should be provided. Even for systems intended for fully autonomous operational deployments, during the early stages of developmental tests, the human ability to react to unforeseen circumstances can only be used if this system allows for human input. A system designed with the possibility of human control blending must provide sufficient useful information displayed to the human such that timely monitoring and control can take place. This inclusion of the human yields a system design with improved robustness; therefore, the likelihood of such a system being successful in its developmental testing is greatly increased.

Ensure Graceful Assumption of Control

With human blending capabilities, the system should provide for graceful assumption of control by the human operator. Displays must be sufficient to provide dynamic information

such that the human can begin to make control inputs without being out of phase with the vehicle response.

5.2 Vehicle Design Tradeoffs

At the time of vehicle design tradeoffs, assessments should be made relative to the full range of human operator involvement in vehicle control. Considerations should encompass (1) the degree to which large uncertainty in vehicle environment might be encountered and (2) the necessity to overfly populated areas.

5.2.1 Managing Uncertainty in Vehicle Environment

Uncertainty in vehicle environment can occur when the operational environment departs from the better controlled test environment. It also occurs when the mathematical models of the vehicle environment inadequately represent the actual flight environment.

Human interaction will typically be required when the degree of departure from prior experience at the vehicle configuration level becomes large. Thus, an unusual aerodynamic configuration is more likely to require human operator intervention during the test program than a more conventional aerodynamic configuration.

When the complexity of the mathematical models and systems is necessarily great, there is more likely an increased sensitivity to vehicle component interactions. If some interactions remain unmodeled, the undesirable impact on the vehicle response is usually increased. Thus, the possibility that a human operator must intervene significantly increases.

When the individual technologies are mature, then the integrated set packaged as a vehicle system will probably yield well-behaved characteristics. The corollary to this situation is when some included technologies lack maturity, a greatly increased need for human operator override capabilities in order to have a robust system in the face of environmental uncertainties results.

5.2.2 Testing Beyond Restricted Range

When testing extends outside of protected range, the public exposure to mishaps must be considered. Human operator capability may play an important role in minimizing public exposure.

6. BEST PRACTICES

In many ways, best practices in vehicle design which were developed over many years of piloted aircraft design also apply to uninhabited aircraft design. Attention should be given the overall design approach (make it balanced) and to the potential role of the human operator or pilot. These two topics are addressed in the Balanced Design Approach and Real-Time Choices subsections.

6.1 Balanced Design Approach

A balanced approach should be taken beginning with vehicle and system design, regardless of vehicle control approach selected. This approach should apply to all categories of specialists, including pilots and flight operations personnel. Inclusion of experienced individuals is particularly important during the design phase of autonomous vehicles. Care should also be taken to include all steps in vehicle checkout, especially the inclusion of a full set of validation tests.

6.2 Real-Time Choices

A pilot or operator can provide high-quality, high-integrity, real-time choices (i.e., decide whether or not to intervene) on matters which may be overlooked or are difficult to foresee during the design phase. This decision making can only be translated into value to the program if the design incorporates sufficient capabilities for the pilot or operator to assess system performance. A blended input for corrective action by the pilot or operator should also be incorporated.

Such capabilities should be favored when uncertainties in vehicle modeling are high. As a note of caution, the benefits that can be accrued by such features are likely to be understated or missed in cost-benefit tradeoffs because of the difficulties in translating off-nominal or unmodeled situations into numbers.

7. CONCLUDING REMARKS

The majority of the flight experience in uninhabited vehicles obtained at NASA Dryden Flight Research Center has involved low-speed developmental vehicles. The exception, the Highly Maneuverable Aircraft Technology, occurred 2 decades ago when many of the technologies that are now taken for granted were still promises for some time in the future.

The extension of lessons learned from those flight experiences to the high speeds and operational deployments anticipated in future uninhabited tactical aircraft should be done cautiously. Furthermore, extending lessons learned from developmental testing (as these all were) to operational deployments is an additional major step in application. These extensions should also be done with care.

Finally, the adoption of best practices acquired over years of piloted aircraft experience should be an important part of the design process followed by all uninhabited tactical aircraft design teams.

8. REFERENCES

1. Deets, Dwain A., DeAngelis, V. Michael, and Lux, David P.; *HiMAT Flight Program: Test Results and Program Assessment Overview*, NASA TM-86725, June 1986.

2. Del Frate, John H. and Cosentino, Gary B.; *Recent Flight Test With Uninhabited Aerial Vehicles at the NASA Dryden Flight Research Center*, NASA/TM-1998-206546, April 1998.

3. Del Frate, John H.; "Four Remotely Piloted Aircraft Mishaps—Some Lessons Learned," *Association for Unmanned Vehicle Systems International '96 Proceedings*, Orlando, Florida, July 1996, p.p. 199-208.

4. Walker, Laurence A.; *Flight Testing the X-36 –The Test Pilot's Perspective*, NASA CR-198058, Oct. 1997.

5. Deets, Dwain A. and Brown, Lewis E.; "Wright Brothers Lectureship in Aeronautics: Experience With HiMAT Remotely Piloted Research Vehicle–An Alternate Flight Test Approach," AIAA 86-2754, Oct. 1986.

The Challenge of UAV Supporting Offensive Air Operations

R.A.Frampton

Air Systems Sector,
Defence Evaluation and Research Agency
Farnborough, Hampshire, GU14 0LX,
UK

1. SUMMARY

This paper provides an overview of some of the challenges facing the use of UAV in combat roles. Offensive roles are identified and the suitability of UAV for these discussed. The use of UAV for surveillance, target acquisition and reconnaissance is acknowledged as well established, the roles involving weapon delivery are less defined. The limitations on using UAV in combat roles are not seen dominantly as technical but more operational. The need to define the concept of operations for using UAV in combat is considered vital. Simulation is advocated to establish the viability of combat UAV concepts, conduct performance trade-off studies and to develop appropriate partitioning of control and decision making. Manned and un-manned platforms are seen as being complementary for the foreseeable future with UAV freeing up the manned platforms enabling them to undertake the roles needing flexibility. The major challenge is seen as establishing an environment in which both manned and un-manned platforms can work together effectively and safely.

2. INTRODUCTION

The word "change" is possibly one of the most frequently used words in modern times. We live in an era which has seen major changes in the last 200 years. For those of us in the Defence business we are particularly aware of the changes which have taken place since the end of the cold war. We are more concerned these days with the concepts of "operations other than war", "peace support" and "coalition operations", scenarios which 30 years ago were almost minor considerations. We do not forget, however, the Gulf war and recognise that the world is still a very unstable place in which military operations are, sadly only too common. Offensive air operations need to be considered in this changing world, it is all too easy for us still to consider large scale war as the only scenario for offensive operations.

Changes in technology have also been dramatic, driven in the last fifty years by the cold war, the space race and more recently by the information explosion brought about by computing and communications advances. The technology advances particularly in processing, software, communications, control and sensor systems have dramatically improved un-manned air vehicle (UAV) capabilities.

Un-manned air vehicles (UAV) have been a part of the military research scene almost since aviation began. Few reached operational service and less did so with much distinction, however that situation has changed. The use of UAV in Israel, Pioneer in the Gulf and more recently and publicly the use of Predator in Bosnia has shown there is a real contribution to be made by UAV in modern warfare. The primary use of UAV has been in the surveillance role. This paper considers the use of UAV in military operations with particular reference to offensive operations. In this context offensive operations covers the whole spectrum of operations from the attack of hard targets in a war situation through to attack of artillery in peace support.

The "challenge" in the title of this paper refers to both the challenges which face the military operator in the use of UAV and the potential challenge to the use of manned aircraft posed by the use of UAV.

3. MILITARY OPERATIONS

3.1 Air-To-Ground

It has been customary to describe offensive air operations in categories such as :

Airborne interdiction (AI)
Offensive counter air (OCA)
Close air support (CAS)
Battlefield air interdiction (BAI)
Suppression of enemy air defence (SEAD)

Paper presented at the AGARD MSP Symposium on "System Design Considerations for Unmanned Tactical Aircraft (UTA)", held in Athens, Greece, 7-9 October 1997, and published in CP-594.

It is important for the military researcher to recognise that the weapons system being considered has to be evaluated for its effectiveness against the military objective and this is more readily apparent if the system is considered in terms of its military function. Defence research within UK has been structured around military functions for a number of years into Research Packages which deal with particular functions to ensure the research is judged in terms of its improvement to the military capability not just improvement to technology. For this paper, however, I will consider the offensive role based more on targets than on the operational categories. This reflects the utility of UAV and illustrates the significance of the diversity of conflicts in which UAV could be deployed.

The offensive targets can be categorised as follows :

Air-to-ground
- fixed targets
- short dwell time targets
- mobile targets
- SEAD targets

Within the air-to-ground category there are sub categories relating to the hardness of the target, for example very hard buried targets or relatively soft buildings, armour or soft skinned vehicles. Categorising by target is not sufficient. A tank in a school yard is a very different target to a tank in a group in an open desert or camouflaged at the edge of a wood. The term being more commonly used to describe the target is "target situation". The definition of the target, where it is in relation to other features, particularly civilian ones is vital for peace support and similar operation where the risk of collateral damage has to be assessed in planning the mission.

3.2 UAV role

Having identified there is a wide spectrum of target situations, the next consideration is the role UAV can play in the attack of targets within a given situation

UAV Roles :

- Reconnaissance/surveillance
- Target acquisition
- Target designation
- Weapon delivery
- Damage assessment
- Data relay

Reconnaissance and surveillance are the dominant current roles for UAV. The use of UAV for surveillance is accepted as a vital part of offensive missions and this role has been widely reported.

Target acquisition extends the reconnaissance role to enable targets to be detected, recognised and their locations passed to planning cells for prosecution of attack. This is the first opportunity to consider the more aggressive use of the UAV. Having a UAV platform in the vicinity of the target opens the possibility that the UAV could designate the target for attack by a weapon delivered by an offensive aircraft. Taking the argument one step further the UAV itself could carry the weapon or designate for a weapon delivered from another UAV. The replacement of manned aircraft as weapons delivery platforms then becomes a logical extrapolation of current UAV usage.

Having delivered the weapons it is vital that the damage inflicted is assessed, for key targets rapid re-attack may be required. In this category of post attack reconnaissance, UAV are potentially well suited to replacing manned aircraft for tactical reconnaissance.

The information from reconnaissance assets needs to be available to the assessors and planners. This information may well be generated by platforms beyond line of sight of the intended recipient and the use of data relays is a powerful role for UAV when satellite based assets are not available.

Of the roles indicated above, it is the weapon direction and delivery roles which are the most challenging.

3.3 Air combat operations

Perhaps the most controversial use of the UAV is in air-to-air combat which is viewed by some as science fiction or at least so far into the future as not to warrant serious consideration at present. Potential roles are unmanned escort for penetrating platforms, unmanned escorts supporting large fixed wing assets such as airborne early warning or surveillance command and control aircraft or fighters in offensive and defensive roles such as combat air patrol.

There are really two drivers which support the case for unmanned air combat aircraft. The first is long endurance for situations in which manned aircraft would be unable to sustain effective operation, the other is survivability. In this latter case the unmanned aircraft should have an extended performance envelope not constrained by the physical limitations of a pilot which can endow the platform with greater survivability in air combat. Reduced cost is potentially also a factor in the use of UAV in combat.

4. STATUS OF TECHNOLOGY

Above I have outlined potential roles for UAV in combat. The advanced cruise missiles available today demonstrate the ability to control, navigate and deliver

weapons autonomously to precise targets. Air combat aircraft exploit high manoeuvre capabilities through advanced digital flight control systems to give a capability pilots could not hope to achieve through manually controlled flight. There are issues as to how far one can push aspects of the technology, for example: Is the ultimate manoeuvrability limited by the propulsion system ? In general it is reasonable to assume combat UAV platforms can be designed at moderate risk.

Environmental factors can still give difficulties, particularly for smaller UAV. The operational requirements will determine whether "all weather" or "adverse weather" capabilities are needed. In either case the risks of icing dictates the use of robust anti-icing systems which still provide a considerable problem for the designer. The ability to accommodate high wind during the mission, at takeoff/launch and landing/recovery is a system design driver. Potentially the most significant environmental factor is the "visibility" of sensor systems. High resolution imaging infra-red (IIR) sensors are capable of excellent imagery but are limited in range by adverse atmospheric conditions. All weather operation, especially from altitude dictates the use of radar, dominantly synthetic aperture (SAR) for ground targets with moving target indication (MTI) for use against mobile targets. Technology is pushing the size down and capability up for these radar systems but for target recognition the higher resolution IIR is more effective in situations where range is not an issue.

Although there are technology risks associated with the use of UAV in combat, which will need to be overcome, it is considered in future the underpinning technology is likely to pose less of a risk than the system and operational issues.

5. UAV AS WEAPON PLATFORMS.

I have outlined above potential roles for UAV in offensive operations. The operations given are currently conducted by manned aircraft, why therefore consider using UAV for these roles? It is suggested the benefits offered by UAV which influence their use in any particular role are :

increased survivability
reduced aircrew risk
longer endurance
supports high tempo operations
reduced cost

On the negative side UAV are

less flexible
less intelligent
vulnerable to countermeasures
limited by rules of engagement
less well understood

From these considerations the attraction for the use of UAV in combat lie in :

situations where there is high risk to aircrew - high is relative to the conflict, the loss of even one airman may be politically unacceptable in peace keeping operations

high threat environments and

a need to be free of the physical limitations imposed by the aircrew.

The use of UAV in the SEAD role is a typical example of a high threat environment and one in which it may well be advantageous to be able to maintain a long term presence. Similarly the location and attack of short dwell time high value targets is a role potentially well suited to the UAV.

Less well defined are the roles involving the attack of fixed targets. In this context, in addition to attack from manned aircraft, there is a trade off between the use of UAV and the use of stand-off missiles either surface or air launched. This trade off is a function of the threat, target situation, platform payloads and operational factors. The use of UAV against fixed targets has yet to be established as an efficient option. The use of UAV for mobile attack is considered in Reference 1.

For target situations where there is high risk of unacceptable collateral damage, for example in peace support, it is suggested that the need for a man in the cockpit will remain for the foreseeable future.

Consideration of the relative issues associated with the use of UAV in combat it is clear that there are roles which UAV can perform and these are in the main the most hazardous roles such as SEAD. There are other roles where UAV complement the use of manned aircraft depending on target situation.

There is a lack of understanding of how manned and unmanned aircraft could work together in missions. There are the obvious air space management issues which need to be addressed wherever UAV are to be operated but co-operation requires more than this. Manned operations are performed by teams who have the benefit of shared training, mutual understanding and a high level of communication. Manned operations in conjunction with missiles are straightforward in so much as the missile is largely pre-programmed to undertake a particular task, UAV will differ in this respect in that they will have a level of autonomy and some decision making powers. This decision making has to be integrated into the offensive "team".

To illustrate some of the issues which arise from UAV delivering weapons consider the following control concepts:

Remotely piloted vehicles
Outer-loop remote control
Task controlled
Autonomous with over-ride

At its simplest level a combat UAV could be totally controlled as a remotely piloted vehicle flown by a remote pilot with a joystick. This approach was used in early UAV used for surveillance but has largely been superseded by increasing autonomy within the vehicle. It is suggested the demands on the data link, operator workload, the need for an extremely high level of situation awareness and pilot skill make this impractical for virtually all combat situations.

The outer loop control situation is one in which the vehicle has an autopilot system controlling the vehicle with high level direction being given by the remote pilot. Direction could be in the form of waypoints. All weapon delivery would be under the total control of the remote pilot in terms of target confirmation from sensor data, delivery authority and post delivery actions. A high integrity wide bandwidth data link has to be maintained at the critical phase of the mission. High quality imagery is required by the operator.

A task controlled UAV would be akin to a re-usable missile. It would be tasked to engage specific targets and given the authority to engage them autonomously (subject to pre-defined confidence limits on target recognition). The UAV would have decision making capability which would enable it to operate without direct communication with the operator at the time of weapon engagement. This gives a capability which is less vulnerable to data link countermeasures, terrain and range limitations. It does however raise the issue of rules of engagement.

The final category considered is the autonomous UAV which could be sent to an area to seek targets, for example SEAD targets. The extent of its authority to engage these could be determined by the controller and adapted to suit the circumstances. This generates a system which is highly robust against data link countermeasures but again raises the issue of rules of engagement.

The above examples do not cover all possibilities but serve to show there is a direct trade-off between the level of autonomy given to the UAV and the demands on the data link. The more significant issue though is the extent to which rules of engagement will dictate the final decision to engage the target has to be made by the operator rather than the UAV.

A further aspects which arise from the above examples is the degree of situation awareness needed by the operator to ensure a successful mission, this is closely linked to the extent of UAV autonomy. The balance between autonomous control by the vehicle and the level of operator control needs to be established. This balance may not be too difficult to define for UAV operated in isolation but operation in conjunction with manned platforms significantly complicates the situation. The issue is best illustrated in the air-to-air context. In the scenario where an air-to-air engagement involves manned aircraft and robotic wing-men, the crew in manned aircraft have the benefit of shared training, high levels of communication and mutual understanding. They know how each other will react and rapidly communicate to confirm intentions. The introduction of un-manned platforms into this scenario now gives greater uncertainty and risk, the natural reaction will be to separate the manned and un-manned platforms with the manned platforms being re-active to to the UAV actions rather than working with them. At this stage, it is not possible to quantify the processes or manner in which a team with robotic members would operate - nor indeed its effectiveness. Intuitively the introduction of highly agile platforms prepared to accept higher risks will dramatically change air combat in favour of the UAV operator, however this has yet to be substantiated .

6. CONCEPT EVALUATION

To understand the use of UAV it is vital that a concept of operations (CONOPS) for the UAV is established for each role. Without this it is not possible to evaluate the effectiveness of the UAV in the role and the capability required from the UAV. As stated above the suitability of UAV for combat is not so much technical but operational, because technology allows it to be done does not make a concept operationally viable or effective.

Conventional operational analysis and studies can be undertaken to evaluate the role of UAV in conflicts but other techniques are required to establish the concept of operations and to address issues such as the level of autonomy to be given to UAV.

Since the construction of real prototype UAV to evaluate concepts is prohibitively expensive an alternative technique being proposed currently within the Defence Evaluation and Research Agency (DERA) is the concept of evaluating "virtual vehicles" in a synthetic environment. The approach is to fast prototype a computer model of the platform based on a system developed to design and validate flight control systems. This virtual prototype is then evaluated in a man-in-the-loop simulation facility such as DERA's JOUST or

RTAVS to establish the concept of operations. Technical issues such as the level of autonomy and the manoeuvre capability required can be readily evaluated by changing the virtual vehicle or the man machine interface. The technique allows for design iterations in a cost effective way. Advanced concepts can be evaluated using sub-scale models in wind tunnels and the data used within the virtual vehicle model environment. Developments in the protocols for linking processors (DIS links) and fast networking capabilities enable simulators on different sites to be connected to take advantage of a range of capabilities.

7. OTHER ISSUES

It has not been possible in this short paper to cover all the issues associated with combat UAV however, it is appropriate to review some of the studies which need to be undertaken to establish the combat UAV role.

Training is a complex issue. Training costs for front line pilots are high as a state of readiness is required which can only be maintained by hands on experience. This also consumes aircraft flying hours and support resources. But what are the training requirements for operation of combat UAV ? Will it be sufficient to train using the form of synthetic environment outlined above - possibly yes for UAV which operate alone but almost certainly not for UAV used in conjunction with manned aircraft. It is necessary therefore to assess training needs as an integral part of the concept evaluation.

Air space management covering the air traffic control requirements and military control is a hot topic for surveillance UAV. The issue will need to be addressed further in the context of weapon carrying UAV which may have more stringent requirements placed on them than the surveillance vehicles.

Reliability standards will need to be defined for combat UAV, it may not be appropriate just to consider reliability as a financial issue, there may be significant safety aspects which now have to be considered. The situation is similar to that in which stand-off missiles fly back home if the mission is not successful - clearly this raises a number of safety concerns.

8. CONCLUSIONS

There are roles for UAV in support of offensive operations. Surveillance, reconnaissance and target acquisition are vital roles for which UAV have already established a presence. Additional to this the ability to relay data and to perform tactical reconnaissance immediately after a strike are roles yet to be exploited. There are also roles for UAV as weapon delivery platforms. The most promising are in high threat environments such as is found in the SEAD role and in applications where the endurance and quick reaction time are important such as the location of high value short dwell time targets. Given the continued advances in technology, it is suggested the main challenges facing UAV in combat are operational more than technical. Concepts of operation need to be established for all combat UAV roles and effectiveness of UAV judged in the context of acceptable CONOPS. Advanced simulation environments should be used to evaluate the concepts. Manned and un-manned platforms can be used to complement each other in combat, the main challenge is to establish safe, robust ways of operating together.

9. REFERENCES :

Reference 1. Stewart.B, Stockel.P "Operational Effectiveness of UCAV in Mobile Target Attack" AGARD MSP 8th Symposium, October 1997, Paper 5.

10. CLASSIFICATION.

UN-CLASSIFIED

This paper represents the views of the author, it does not necessarily represent the official views of the Defence Evaluation and Research Agency nor the UK MOD.

AUTOPILOT SYNTHESIS FOR UNMANNED TACTICAL AIR VEHICLES (UTAV)

P. Faggion
L. Zolla

ALENIA Difesa
Avionic Systems and Equipment Division
Strada Aerroporto, 10072 San Maurizio C.se (Torino), Italy.
Tel. (39)11-9967 817; Fax (39)11-9967 694

SUMMARY

This paper presents an overview on the AutoPilot design philosophy for a medium class, jet powered Unmanned Tactical Air Vehicle (U.T.A.V.) and the development of its Rig + Advanced Integrated Data Acquisition & Simulation System (Rig + AIDASS). After a short description of the Mirach 150 U.T.A.V. system, the synthesis methodology of the primary control laws for the steering and navigational modes are presented (Autopilot and Flight Management System). The process aims at verifying accordance between requirements and performances of the global system (Autopilot+Airframe). The performances of the system are shown: dynamic responses in front of altitude, groundspeed and heading demands and their maintenance in presence of atmospheric turbulence (MIL-F-8785/C). The study is developed in FORTRAN 77 language.

LIST OF SYMBOLS AND ABBREVIATIONS

6DOF	6 Degree Of Freedom
ADC	Air Data Computer
AHRS	Attitude and Heading Reference System
AIDASS	Advanced Integrated Data Acquisition & Simulation System
AP	Autopilot
δ_a	Aileron deflection angle
δ_e	Elevator deflection angle
FMS	Flight Management System
GPS	Global Positioning System
IAS	Indicated Air Speed
p	Roll rate
q	Pitch rate
SAS	Stability Augmentation System
TAS	True Air Speed

KEYWORDS

AutoPilot, PI Control Laws, Self Tuning, Unmanned Tactical Air Vehicles, Simulation.

1. INTRODUCTION

Herein are presented the main steps of the design methodology employed for the Mirach 150 FMS/AP project development. MIRACH 150 is an ALENIA's carrying out for the Italian Army: a high speed Unmanned Tactical Air Vehicle derivative of the MIRACH 100 target drones family.
The procedure herein described is completely computer-aided to simulate the behaviour and performances theoretically achieved at the end of the design phase.

First of all, a mathematical model of the airframe+sensors has been implemented on a VAX computer, based upon airframe and equipment suppliers' database; then, the classical Equations of motion have been implemented to build a real 6 Degree Of Freedom (6DOF) Model.
The third step consisted in the linearisation of the motion equations to extract the transfer functions needed to outline the autopilot loops: the inner loop Stability Augmentation System (SAS), the attitude autopilot, and then the outer loop: the steering and navigational autopilot.
These control laws have been subsequently implemented on the 6DOF model to evaluate their response in a test and trial sharpening process.
In order to evaluate the performances of the whole UTAV+FMS/AP system, an Avionic Integration System called Rig has been developed. It is made up of a phisical bench, on which lies the UTAV and its avionic equipment and an AIDASS which acquires all the data to be monitorized, and simulates the motion and external environment.

2. MIRACH 150 UTAV SYSTEM

The UAV on which this survey is based belongs to the MIDI cathegory, whose main views are shown in Figure 1.

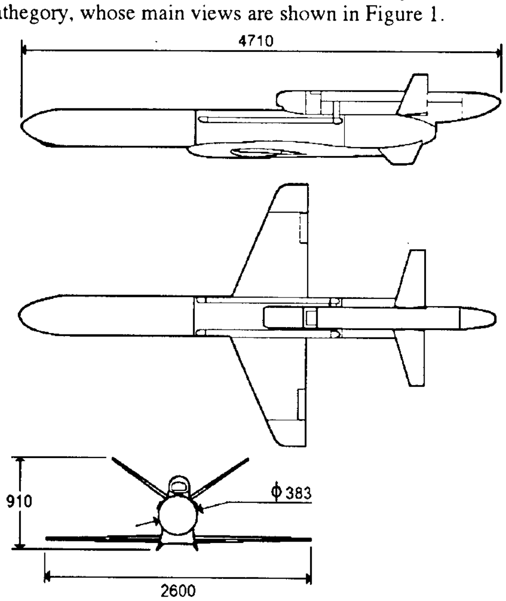


Figure 1: M-150 main wiews.

The air vehicle features a round fuselage containing the payloads, fuel tank and the engine, which is a turbojet engine with low by-pass ratio; above the fuselage is located the air in-take. The wing, located in the backward section of the fuselage, has thin sections, positive sweep on the leading edge and null sweep on the trailing edge, low aspect-ratio and

Paper presented at the AGARD MSP Symposium on "System Design Considerations for Unmanned Tactical Aircraft (UTA)", held in Athens, Greece, 7-9 October 1997, and published in CP-594.

ailerons for control on the roll axis; the main feature of the air vehicle is its unconventional tail, which is in form of a V; the movable part of this tail can be controlled only with symmetrical motion, to obtain control on the pitch axis (it functions as an elevator), the turning of the vehicle is obtained only by rolling the plane with the ailerons.
The mathematical model has been developed from a data-base documenting every single subsystem: it was modelized:
Aerodynamics,
Mass properties,
Turbojet engine,
Actuators group,
Avionic sensors: Attitude and Heading Reference System (AHRS), Air Data Computer (ADC), Global Positioning System (GPS),
External environment.

3. MATHEMATICAL MODEL, MOTION EQUATIONS AND THEIR LINEARISATION

The differential equations describing an airplane motion, in their most general form, are composed of a system of nine equations and nine unknowns; this system has been explicitated and re-written to present every single unknown in only one equation, so it is possible to solve each equation separately with numerical methods like the Adam-Bashford 2nd order one.
The differential equation system might be furtherly simplyfied considering a series of hypotesis on the airplane and the variables which perturbate its trim status; this operation is called linearization of the motion equations. The starting point for this operation is a steady trim condition for the airplane, around which it will be evaluated a simplifyed desciption of its evolution. The steps to write the motion equations and for the following linearization are here exposed:
I The airplane is considered as a stiff body.
II The airplane mass and its distribution are intended steady.
III The airplane holds the XZ plane as a symmetry plane.
IV The gyroscopic effects of all the moving rotors (compressor and turbine stages) are considered irrelevant into the motion equations.
V The airplane is supposed in a steady state and the parameters of this state are perturbed by little variations.
VI The motion in the longitudinal plane is not influential over the motion into the lateral-directional plane and vice-versa (uncoupled planes).
VII The environmental parameters variations are considered irrelevant if the altitude variations of the airplane are small during the motion.
VIII The turbojet thrust is supposed to be aligned with the X body axis.
With the linearization operation a system of linear differential motion equations is obtained, from this system it is possible to represent the motion by a first order differential equations system called the "status equations", in which the principal and most interesting parameters are explicitated. The status equations, disassembled into separate equations and explicitated for the parameters under evaluation, give the *transfer functions*, by which it is possible to study the architecture of the control system.

4. SAS DEVELOPMENT

The SAS is that part of an aircraft Autopilot (historically the first to be realized) that damps oscillations around pitch, roll and yaw axes by means of contrasting aerodynamic moments produced by rotation of control surfaces.
On the ground of aircraft configuration, SAS damps longitudinal and lateral oscillations induced by manoeuvre and possible disturbs: in the linear model each of the damper loops are separately studied (see ref. 1 for further details). Then the two loops are studied by means of root locus, polar and Bode diagrams to estimate their stability; the Gain and Phase margins are evaluated both on Bode and polar diagrams (by means of Nyquist principle).
When the most satisfactory feedback design is defined, this will be optimized by implementing it in the aircraft linear and 6DOF models over the whole flight envelope.

4.1 Pitch Damper (Longitudinal oscillations damper)

The device acquires body-axes pitch rate q and opposes it in case of high-frequency oscillations, instead it keeps idle in case of null or low-frequency oscillations; Pitch Damper works by means of elevator and so the $q/\delta e$ aircraft transfer function will be used for estimating the Damper performance.

4.2 Roll Damper (Lateral oscillations damper)

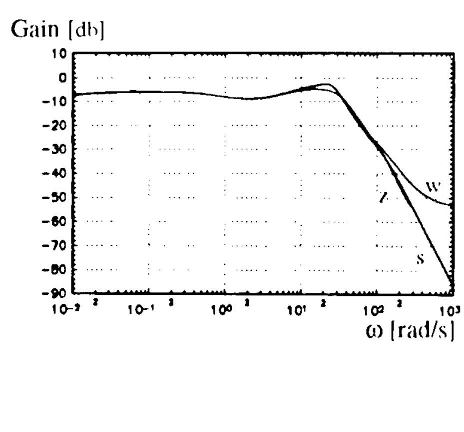
The device acquires oscillations of body-axes roll rate p and opposes it by means of asymmetrical manoeuvre of ailerons in case of high-frequency oscillation, therefore $p/\delta a$ aircraft transfer function will be used for estimating the Damper performance.

4.3 Z and W transfer function analysis

Control loops analysis and synthesis in linearized system has been founded on continuous transfer function in s complex variable, that is Laplace transform.
To obtain a better confidence in the analysis made by means of Laplace transforms, confidence already obtained comparing linearized model and 6DOF model, z and w transfer function analysis has been performed.

4.4 Pitch and Roll damping loops

Investigating the responses of the two damper loops that are part of the Autopilot, it can be reported that sufficient damping ratio and sufficient response rate have not been achieved, in spite of optimization of time constants.
One of the possible solutions concerns a second feedback loop of the quantity controlled by Dampers. It has been chosen for its advantages: it is simpler to realize and less burdensome for the AP microprocessor. The new outer loop, named Damping loop, is characterized by unitary gain and only one block for sensors simulation.
The transfer functions of these two loops have been analyzed too by means of Laplace transforms (s) and discrete transforms (namely z and w): the results of this frequency analysis is shown in Figure 2 and Figure 3 for Pitch and Roll Damping separately (see ref. 2 for further details).
Figure 2 shows the Bode diagrams (Gain and Phase) for Pitch Damping loop in s, z and w. Figure 3 holds the same for Roll Damping loop.



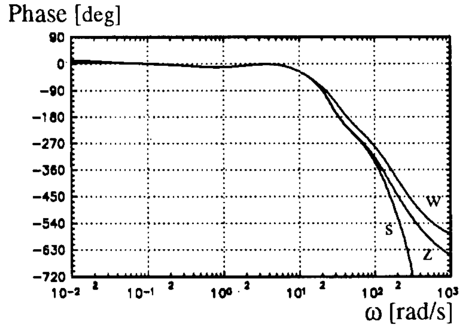


Figure 2: Pitch Damping frequency analysis.

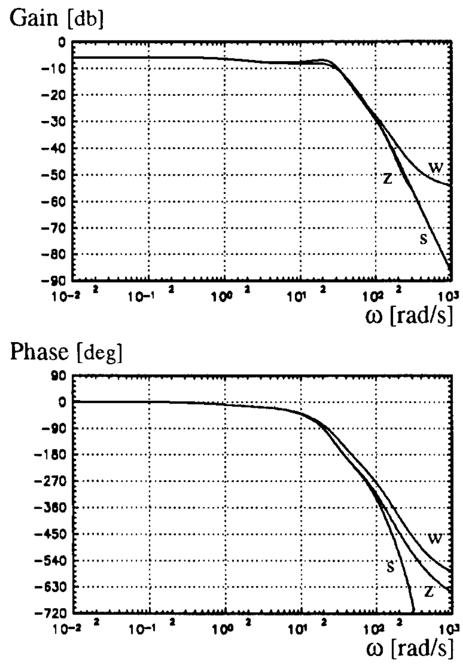


Figure 3: Roll Damping frequency analysis

5. ATTITUDE AUTOPILOT DEVELOPMENT

5.1 Pitch Acquire and Hold.

The device acquires and holds pitch angle: when the aircraft has to climb to achieve altitude or to level after a dive for example, the desired pitch angle is commanded from FMS/AP. Comparing commanded pitch angle with measured pitch angle, the input pitch rate q *demanded* for SAS is calculated (by means of a multiplying constant); in response to the SAS demand, an *actuated* q is returned, which (considering transfer function θ/q) will generate an *actuated* θ. Pitch Acquire and Hold loop, shown in Figure 4, is obtained by means of a feedback design of θ *actuated* that is measured by sensors separately (see ref. 2 for further details).

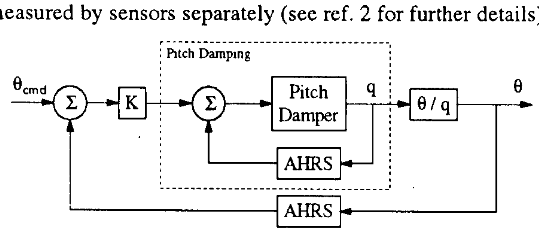


Figure 4: Pitch Acquire & hold loop.

5.2 Roll Acquire and Hold

The lateral and directional channel is controlled by this loop that acquires and holds roll angle: since the conceptual design criteria for this operation are the same of Pitch Acquire and Hold control loop, the architecture and development methodology are the same too. In this case the ϕ/p transfer function has been taken into account.
The system Damper + Damping + Acquire and Hold obtained in this way, reduces the time to achieve regime condition and increases oscillations damping.

5.3 Control Laws optimization

Once the control loops have been designed, an optimization of the internal parameters is necessary to guarantee the best performances in the whole flight envelope. For this reason, evaluations both on linearized and 6DOF models have been thoroughly conducted.

6. STEERING AUTOPILOT

Once the attitude autopilot has reached its final design and has undergone evaluation tests, the steering autopilot can be dealt with.
In the Steering mode, the autopilot generates three commands: altitude, groundspeed and roll; to acquire and hold the commanded values of the flight parameters, a different loop for each has been designed. In the particular case of altitude, two different loops have been studied, implemented and tested: one for acquiring altitude, the other to hold it.
Given the measured flight altitude, a sector (with variable limits) above and under it has been defined: if the commanded altitude is within this sector, the autopilot activates the Altitude Hold mode, otherwise it reverts to Altitude Acquire mode. This differentiation comes from the necessity to guarantee flight safety over acquiring different altitudes in different flight conditions.
In the Altitude Hold mode, besides the altitude loop, the *groundspeed* and *roll acquire and hold* loops are contemporarily active; instead, in the Altitude Acquire mode, only the *roll acquire and hold* loop is active.

6.1 Altitude Hold loop

The *altitude hold* loop operates by means of the elevator to hold the commanded altitude. The starting point of the design process is the Vertical velocity / pitch rate transfer function, around which the whole linearized model will be built.
The *altitude hold* loop is made up of an inner loop (formally a damper loop) and of an outer loop (which is referred to as a position loop).
On analysing the linear inner loop, it can be found that is based upon the Vertical Velocity/q transfer function: to obtain the desired Vertical Velocity a Pitch rate is demanded, therefore (through the Pitch damping loop) an elevator rotation is commanded.
The outer loop is therefore based upon the h/Vertical Velocity transfer function.
In this way it is clear that, to hold a certain altitude (or to acquire an altitude not much different from the current one) the final command is an elevator one.

6.2 Groundspeed Acquire and Hold loop

The *groundspeed acquire and hold* loop, as the *altitude hold* loop, is composed of an inner loop and an outer loop.
The linear inner loop is based upon the Groundspeed derivative/Throttle command transfer function.

As it was foreseen by harmonic analysis, and later confirmed by 6DOF simulation, this is not a fast response loop, since the normal turbojet reaction time to a throttle command is not so quick.
Anyway it has been preferred a slower but more precise loop to a design which gave precedence to fast response, but which allowed Groundspeed oscillations around the commanded value. By the way this also helped to prevent compressor and turbine problems in the turbojet, related to sudden and violent shifts in throttle command.

6.3 Roll Acquire and Hold loop

The *Roll acquire and hold* loop here referred to, is the same described in the Attitude autopilot.

6.4 Altitude Acquire loop

The *Altitude acquire* loop has been designed on a completely different approach from the *Altitude hold*: first of all, the best climb and dive pitch attitudes have been evaluated, then on these grounds optimal climb and dive IAS have been calculated.
Once obtained the climb and dive speeds, it has been chosen to acquire and hold them by the elevator rotation. In this way, the necessary steps to climb or dive are: calculate the IAS commands (which are a function of the actual altitude), then acquire and hold them.

6.4.1 IAS Acquire and Hold loop

In order to achieve the correct climb or dive speed while effectively climbing or diving, it has been decided to achieve this velocity by means of elevator command.
Since the climbing speed is slightly lower than the IAS corresponding to the lowest programmable groundspeed, it's obvious that a slower velocity can be achieved only by climbing; similarly, since the diving velocity is only a few m/s above the highest horizontal velocity, to achieve this velocity the UTAV effectively dives.
It must be noticed that, to account for roll manoeuvres while in Hold mode, the lowest programmable groundspeed has been limited to a value slightly greater than the calculated stalling TAS for maximum roll.
Speaking of the actual loop design, it can be said that it is similar to the *altitude hold* loop: there are two nested loops.
The outer loop compares commanded IAS with actual IAS and, via a scheduled gain, demands an acceleration (IAS derivative); the inner loop compares the demanded acceleration with current one and, through another scheduled gain, demands a pitch rate which is given as input to the pitch damping loop.

6.5 Control Laws optimization

The optimization of the first three loops (*altitude hold, groundspeed acquire and hold, roll acquire and hold*) has been conducted on linearized model and then on the 6DOF model, as seen before for the Attitude autopilot loops.
The optimization of the *IAS acquire* loop, given its high degree of non-linearity, has been studied and optimized directly on the 6DOF model.

7. GUIDANCE AUTOPILOT

Once the main loops for the Steering Autopilot have been implemented, optimized and tested, the last part of the autopilot has been faced up.
To better understand the functional mode of the guidance autopilot, herein is a short description of the navigational modes of the M-150 UTAV.

The main phases of the M-150 flight are:

- Launch.
- Navigation (autonomous or remote).
- Recovery.

The Launch phase is intended to safely bring the plane to a preset minimum altitude and groundspeed from which start the mission. In this phase a preselected sequence of pitch and throttle commands are fed to the UTAV actuators, while the ailerons are kept neutral: the whole phase takes place in the longitudinal evolution plane.
Once the Launch phase is terminated, the FMS/AP switches to the Navigation phase and, if the autonomous mode is selected, the flight plan is brought to attention, and the autopilot performs the waypoints acquisition.
This operation is quite complex because there are several differen waypoint types: for the purpose of this study we will explain only type 1 and 2. Type 1 waypoint is the waypoint that must be overflown by the UTAV, then the autopilot can switch to the next one; type 2 waypoint means that the autopilot must link up the actual flight course (connecting the previous waypoint to the next) to the next one (connecting the next waypoint to the following) by turning (track connecting mode).
The Navigation phase might also be carried on by a ground operator: this is the remote mode. In this case the operator can fly the UTAV in Steering mode (altitude, groundspeeed and roll commands) or in Attitude mode (pitch, roll and throttle commands).
Once the last waypoint has been reached (if in autonomous mode) or the recovery command has been sent from the ground operator (if in remote mode), the UTAV disposes itself to be recovered.

7.1 Track Acquire and Hold

Once a waypoint is reached, a new course has to be initialized: by means of latitude and longitude of the previous and next waypoint, plus the spherical correction for the earth's surface (performed according to WGS 72 or WGS 84 earth's models), the actual course's track angle and the direction cosines are calculated. Then, the following navigational parameters are routinely updated:

- Distance along track: the distance, along the line representing the course, from the actual position to the next waypoint
- Distance across track: the distance from the actual position and the line representing the course
- Velocity along track: the actual velocity along the line representing the course
- Velocity across track: orthogonal velocity to the previous one.

Figure 5 better explains the meaning of these parameters.

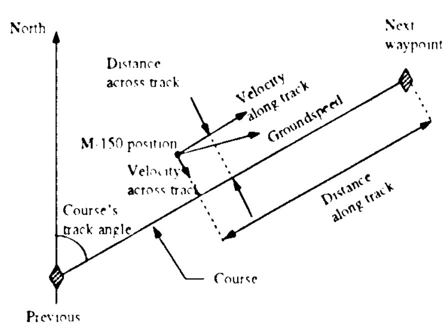


Figure 5: Navigational parameters

The *track acquire and hold* loop is again constituted by an outer loop (position loop) and an inner one (velocity loop).
The outer loop compares the actual distance across track with the desired one (which is 0), and generates (via a scheduled gain) a velocity across track demand.
The inner loop compares the demanded velocity across track with the actual one and generates an appropriate roll command.
The distance along track parameter is evaluated to switch waypoints when it becomes 0 or negative.

7.2 Track Connecting mode

The Track Connecting mode is an intermediate phase between two consecutive courses. When the next waypoint is a *type 2* one, the FMS/AP calculates a turn radius from actual TAS and maximum allowable roll.
Given the turn radius, the distance from the next waypoint (reached which the turn is commanded) can be calculated.
While holding the same commanded altitude and groundspeed of the approaching waypoint, the FMS/AP commands maximum roll to achieve the next course, pointing towards the following waypoint.
This turning state is held until the next course is reached, then the new waypoint's parameters can be brought to attention.

8. ATMOSPHERIC TURBULENCE

For testing the performances of the Autopilot, a model of the statistic turbulence has been implemented as part of the external environment.
Statistic turbulence has been studied by means of Dryden model according to MIL-F-8785/C norm; aircraft has been specifically tested in moderate turbulence alongside the three earth-axes and around the three body-axes for p, q, r angular rates. Diagrams of the perturbation linear velocities (along earth axes) are shown in Figure 6 through Figure 8 .
The performances achieved through turbulence have been compared with flight in calm atmosphere.

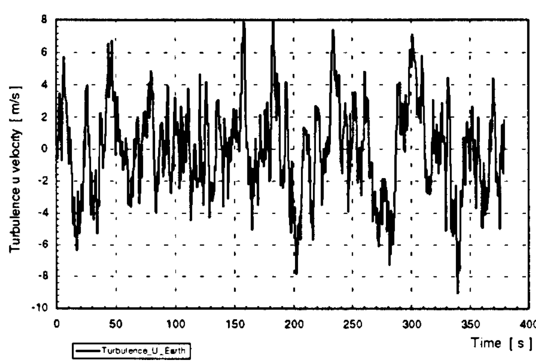


Figure 6: Atmospheric turbulence velocity u

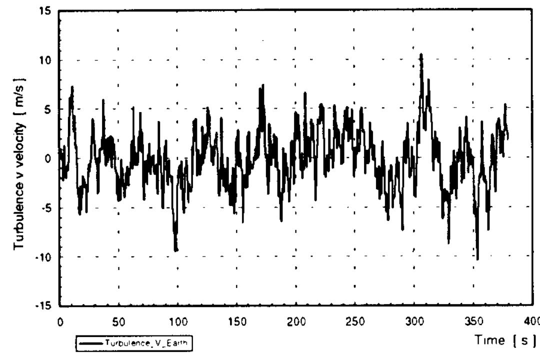


Figure 7: Atmospheric turbulence velocity v

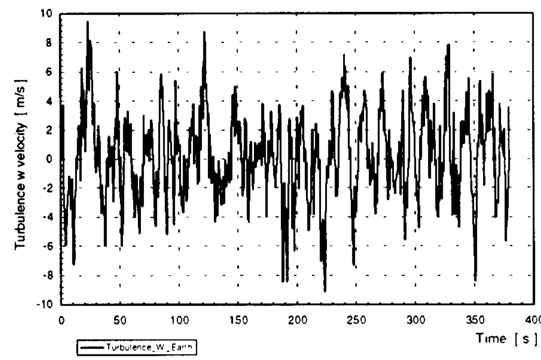


Figure 8: Atmospheric turbulence velocity w

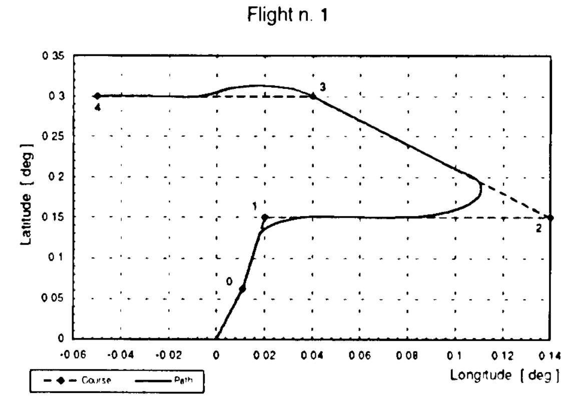
9. UTAV SIMULATED FLIGHT TESTS

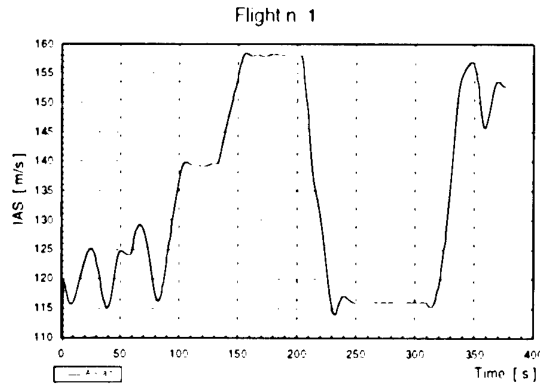
To evaluate the performances of the FMS/AP in its final design review, a series of simulated flight tests have been conducted with various flight plans. Here reported are two similar flights which have been conducted in autonomous mode: the only difference between the two flights lies in the added atmospheric turbulence on flight no. 2, to better evaluate performances in non-ideal flight conditions.
The flight plan (common to both the first and second flight) is the following:

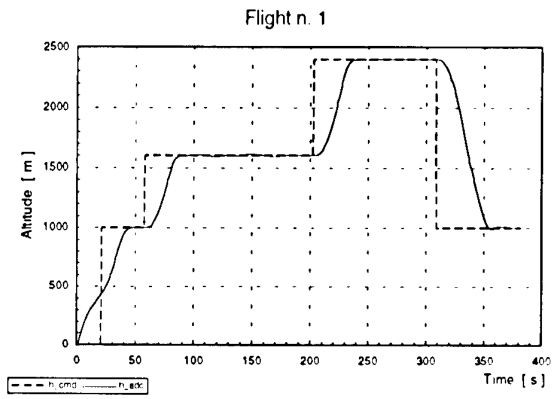
- Launch from an altitude of 0 meters a.s.l. with 10° heading orientation.
- Transition to safe manoeuvre flight condition: 1000 m height above launch altitude and minimum groundspeed of 130 m/s. This must be accomplished disregarding of the route (towards first waypoint) track angle.
- First waypoint acquisition: type 2 waypoint, 0.15° latitude North, 0.02° longitude East, 1600 m altitude, 150 m/s groundspeed.
- Second waypoint acquisition: type 2 waypoint, 0.15° latitude North, 0.14° longitude East, 1600 m altitude, 170 m/s groundspeed.
- Third waypoint acquisition: type 1 waypoint, 0.30° latitude North, 0.04° longitude East, 2400 m altitude, 130 m/s groundspeed.
- Fourth waypoint acquisition: type 1 waypoint, 0.30° latitude North, 0.05° longitude West, 1000 m altitude, 160 m/s groundspeed.
- Istantaneous recovery.

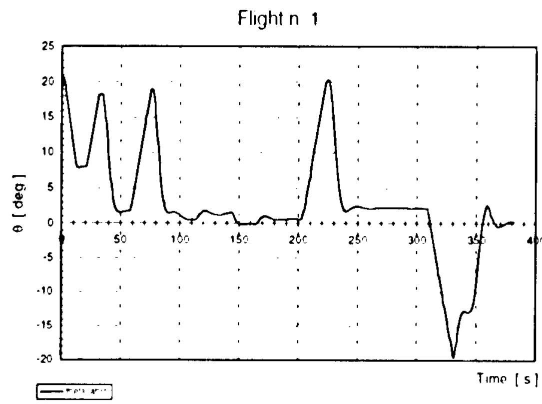
The 0 point in the Latitude vs Longitude charts indicates the transition from launch phase to navigation phase: the safe flight conditions described before have been reached.

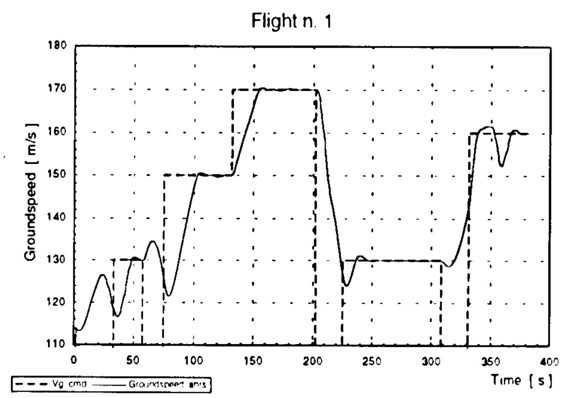
9.1 UTAV Test flight no. 1

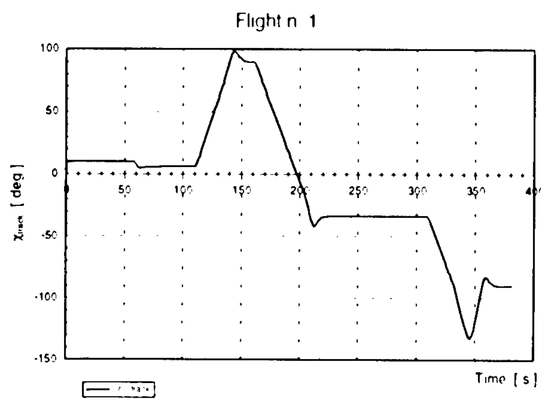


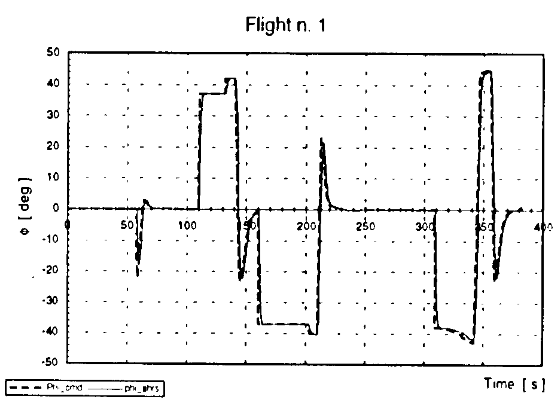


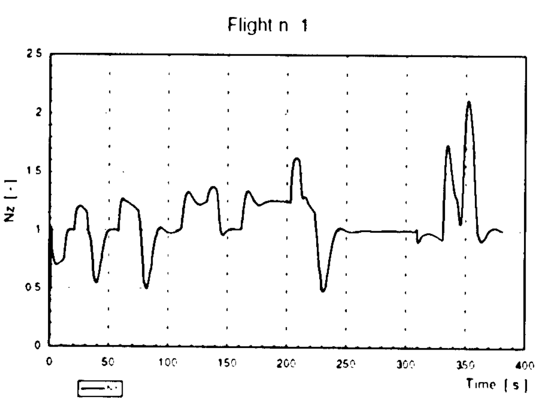




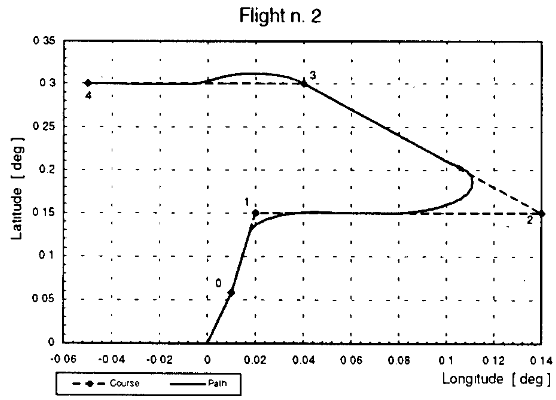


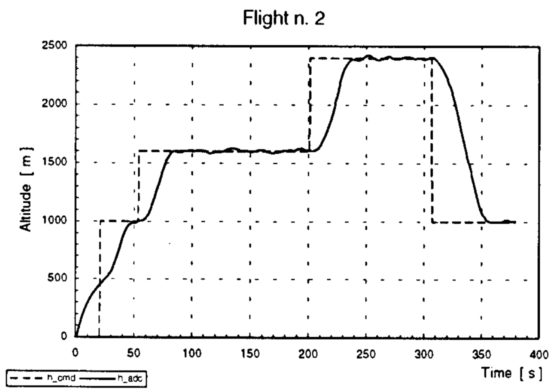


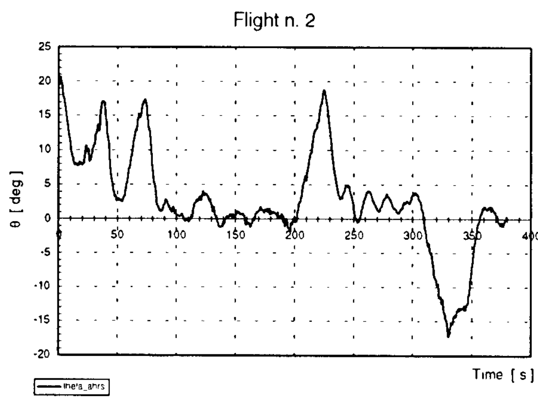


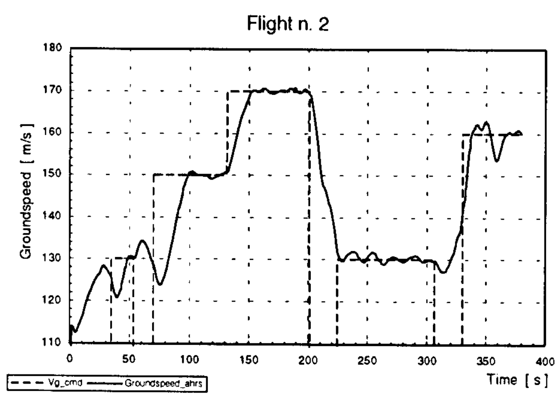


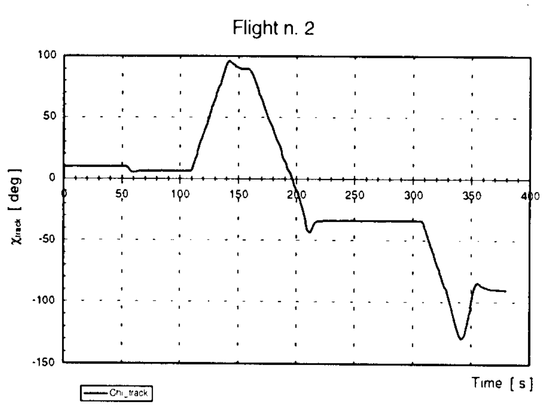
9.2 UTAV Test flight no. 2

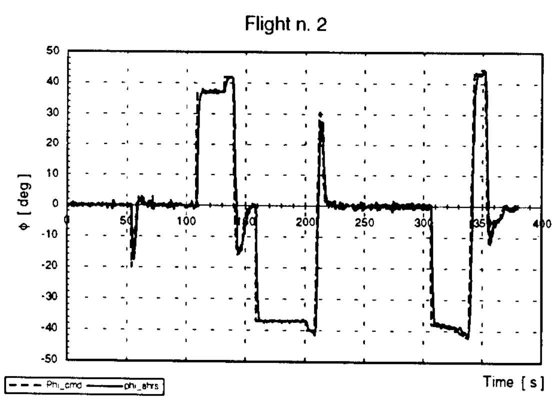


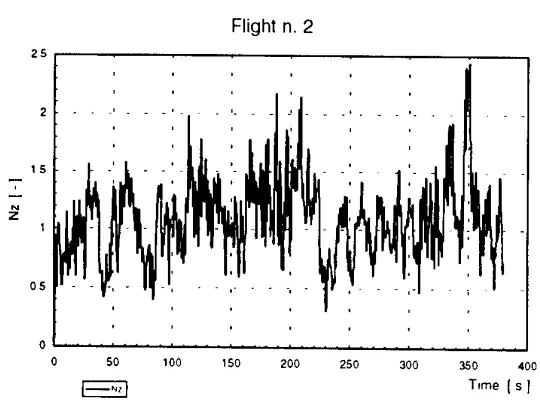












10. RIG - AIDASS FOR M-150

Once completed the design phase of every single sub-system for the M-150, a special tool called Rig has been built to perform ground integration tests and performance evaluations of the real UTAV in a real-time environment.
This Rig has purposely been designed to help in performing the difficult task of integrating the on-board avionic in a step-by-step process: it is in fact possible to simulate those sub-systems and equipments which are intended to be integrated in further steps, allowing at the same time the full functionality of the UTAV avionics.
Rig is made up of a bench and an AIDASS, which stands for Advanced Integrated Data Acquisition and Simulation System.
The bench is composed of a mechanical structure and wirings: the mechanical structure supports all the patch panels of the system channels, the airframe and the equipments, while the wirings allow all the Rig electrical connections.
The AIDASS is a ground equipment simulating the external environment and all the avionic equipments of the UTAV, while collecting all the internal and sensor parameters, it is composed of a mainframe computer (a VAX 6000 computer), a workstation to allow man-machine interface, and an input-output driving system called Front/End.
The whole assembly is better explained in Figure 9.

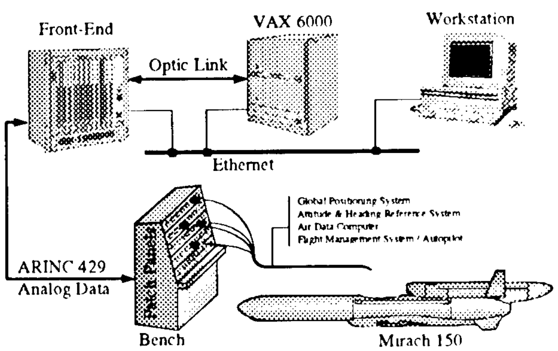


Figure 9: M-150 Rig-AIDASS

On the VAX computer the whole 6DOF mathematical model of the M-150 is implemented as well as the avionic equipment and external environment modelization, while the Front/End manages the whole input-output cards and the data acquisition and recording; the workstation is used to manage and monitor the whole AIDASS and avionic sub-systems functioning.
The peculiarity of the Rig assembly is that it allows real-time simulation and stimulation of the Mirach 150 UTAV; the only drawback is that some avionic systems won't give dynamic output.
For example, since the UTAV lies on a bench, the AHRS sensed parameters (such as linear and angular velocities, attitude angles, geographical position etc.) won't be consistent with the simulation in progress, so they will be substituted (always in real-time) by the calculated ones from the sensors mathematical model running on the VAX computer.
The main advantages of this Rig can be summarized as follows:

- The whole Avionic System can be integrated and tested, and its performances evaluated.
- The programmed flight plan can be ground executed to be proven.
- The flight clearance can be delivered.

11. CONCLUSIONS

The reported work shows that the methodology of Autopilot control laws design criteria, followed by authors, are correct and effective; even if in the peculiarity of the problem that has been taken into consideration, used criteria acquire a significant generality from the methodology point of view and go beyond the specific shown case and are a useful guidance for solution of similar problems.
Upon examinating the Autopilot performances, the included charts show that good damping ratios and response rate for the SAS have been achieved, while the acquire and hold loops (both of the Attitude and Steering Autopilot) perform the commands acquisition in a flawless manner, in spite of mantaining a simple structure. The Guidance Autopilot too shows the same behaviour, even in the case of atmospheric turbulence.
The Rig integration and real-time simulations with hardware in the loop, provide the necessary confidence on the Autopilot performances and the compulsory flight clearance to start the flight tests.

12. REFERENCES

1. L. Borello, P. Faggion, L. Zolla: "Progetto di un sistema di aumento di stabilità + autopilota per velivoli non pilotati", 38° Convegno ANIPLA, Atti del convegno, Perugia (Italy)1994
2. G. Bertoni, L. Borello, P. Faggion, S. Vallino, L. Zolla: "Autopilot synthesis for unmanned air vehicles", 1995 IFAC-IACA Conference, Bejing (Rep. of China), final printings.
3. Beal, T.R. (1993). Digital simulation of atmospheric turbulence for Dryden and Von Karman models. *Journal of Guidance, Control and Dynamics*, Vol. 16 No. 1, pages 132 - 138.

Mission Re-Planning for Standoff Weapons

MARLOW HENNE
SVERDRUP TECHNOLOGY, INC
308 WEST D AVENUE
EGLIN AFB, FLORIDA, 32542
USA

CAPTAIN JAMES H. BAKER
UNITED STATES AIR FORCE
AIR FORCE DEVELOPMENT TEST CENTER
401 WEST CHOCTAHATCHEE
EGLIN AFB, FLORIDA, 32542
USA

I. SUMMARY

This paper frames a general discussion of current air campaign planning methods at the campaign and mission command echelons, and discusses the operational and technical mission re-planning requirements required for standoff weapons to engage fleeting targets or targets discovered immediately before or during a weapons delivery mission. Some weapon systems already have the technology needed to engage this threat; doctrinal advances and allocation of scarce sensor and weapons resources are the driving factors preventing effective fleeting target engagement.

II. Introduction

While this conference addresses unmanned aircraft, certain medium and long range standoff air-to-surface weapons take on many of the same characteristics such as navigation and target detection. Navigation to a target area or attack point must be planned along with target location and characteristics. A typical mission planning session for stand off weapons will address this information. In the heat of battle, new high priority targets may be discovered, known and planned targets may move, or designated targets may be destroyed before weapon launch or the weapon terminal attack phase. In any of these situations, it is desirable to re-plan or redirect the weapon

In order to understand mission re-planning, we must first understand how the mission was originally planned. A close understanding of both the campaign and mission level operations cycle is necessary before considering how and when mission re-planning can occur. Since mission planning and re-planning take place primarily at the command echelons, they will provide our fundamental operational considerations. From these, we will derive some basic technical requirements for engaging the more difficult target types.

III. Planning

We define planning as happening at two distinct levels of command, each operating with very distinct decision sets and timelines for reaching those decisions. Campaign planning includes the theater level planning of overall objectives, sensor and other theater level asset tasking, developing of unit level tasking, and targeting priorities. Mission level operations are concerned with

Paper presented at the AGARD MSP Symposium on "System Design Considerations for Unmanned Tactical Aircraft (UTA)", held in Athens, Greece, 7-9 October 1997, and published in CP-594.

carrying out the actual mission of platform/weapon to target delivery.

In most air campaigns today, there may be several other levels of command hierarchy present, such as the wing, unit, squadron, or base level command. In most cases, these hierarchies are limited to an 'organize-train-equip' role in the modern air war. Only in rare exceptions are they directly involved in target selection. They only provide the resources and infrastructure needed to strike targets. We will consider the flight or force level command hierarchy as being included as part of mission level planning — force packages consisting of one or more platforms directly responsible for carrying out a target strike, supporting a target strike, counter-air over a particular geographic region, or a similar mission.

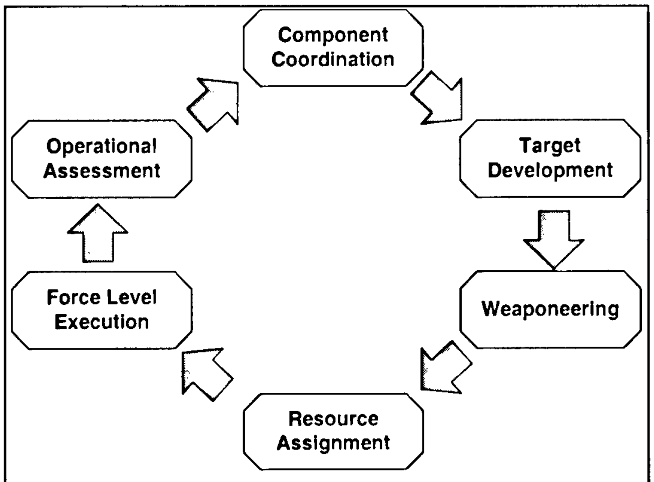


Figure 1 Operations Cycle -- Campaign Level

A. Campaign Level Air Tasking Cycle

The operations cycle at the campaign level generally follows the six steps outlined in figure 1. The purpose of planning at the campaign level is to ensure that joint air operations are carried out both efficiently and effectively. These steps are normally carried out in a centralized location (an Air Operations Center, or similar), with planners, targeteers, intelligence officers, other service, or allied liaisons, and operational experts in the same location as the senior decision-maker. Only the briefest of summaries is given here.[i, ii]

The cycle shown is repetitive and continuous from day to day. In general, there are at least three task orders in planning or review in this cycle at any one time. Today's task order is being carried out, which means that the campaign level personnel are tracking current developments in execution status. They are carrying out the latter two steps of the air tasking cycle. The middle two steps of the air tasking cycle are simultaneously working tomorrow's task order — defining and disseminating mission "solutions" to the problems that were posed in the first two steps which are concerned with more broadly defining the following day's strategic plan and target priorities.

The tasks listed are broad and over-simplified for our use. In reality there is continuous task overlap and information, and personnel are involved in many different phases and sub-tasks.

1. Component Coordination

Initially, the theater commander consults with ground, air, and naval component commanders to review the progress of the warfighting effort, and to provide overall guidance. His component commanders will recommend target sets (and possibly priorities) to meet the theater commander's guidance. The output of the component coordination task is the sortie apportionment, which defines the percentage of available sorties to be used in various air task categories, such counter-air for air superiority, strategic attack, interdiction, or

close air support. This apportionment ensures the most effective use of the limited air resources in support of the theater commander's intent and objectives.

2. Target Development

Each component now brings to the limited air resources a list of prospective targets. After extensive coordination among the staffs, a prioritized target list will be produced, along with supporting guidance, rules of engagement, and other information.

3. Weaponeering

Once a prioritized list of targets and objectives (destroy, damage, neutralize, delay) is available, targeteers define the aircraft/platform/weapon combination most likely to produce the desired result. They will consider aim points, fusing, approach direction, angle of attack, target identification, threat areas, probability of destruction, etc.

Other planners are simultaneously constructing force packages to meet the mission requirements, grouping targets similar in location or nature, and defining support aircraft needed to ensure an individual mission's success. For example, surveillance missions, Suppression of Enemy Air Defense (SEAD) strikes, and electronic warfare missions may all need to be flown prior to, or in conjunction with, an air interdiction mission in one or several regions.

Taken together, the weaponeered (and prioritized) target set, target location, enemy defenses, apportionment decision, and overall guidance will determine roughly the schedule and type of missions needed.

At this time the range and likely release points of the weapons will be considered. While the release point of an unguided direct attack or gravity weapon is a major component of the impact point, guided gravity weapons have guidance kits that allow considerable offset from a purely ballistic strike point. Powered weapons and longer range stand-off weapons fly complete flight paths of many miles on their own after launch.

4. Resource Assignment

Armed with an overall plan of attack for tomorrow's operation, the difficult task of assigning many aircraft from many locations (and possibly services and nationalities) to many different targets begins. They also must define call signs, IFF, frequencies, etc. This process takes anywhere from six hours for a small or routine air campaign to twenty four hours for large or contingency-based operations.

Throughout this time period, other planners work airspace control issues — safe ingress and egress aircraft routes — as well as determine span of control issues for air defense and air control. They also finalize tanker and other support aircraft sorties.

The output of this phase is a set of mission lines, defining to a very explicit level of detail the aircraft/platform/weapons to be used to destroy known aim points of specific targets at specific times. This information is passed to the force level for execution with enough time for unit-level preparation before the first targets are to be struck.

5. Force-Level Execution

This includes all the various and sundry tasks involved with carrying out the resource assignments so meticulously made in the previous task. At the campaign level, combat operations personnel are monitoring current developments and making "real time" modifications to previously published orders based on weather or enemy reactions. They also monitor battle damage assessment and in flight reports.

6. Operational Assessment

The operational assessment phase is where the overall results of the on-going air operation is evaluated, including munitions effectiveness, and recommendations. Planners involved in this task must weight likely enemy courses of action in light of successes to date, and make recommendations to both the air component commander and theater commander as to how to best use current air resources in order to further the campaign objectives. Although it is listed as the last task, it is in a very real sense also the first task, providing the inputs necessary to continue component coordination, target priorities, weaponeering and allocation, and future resource assignments.

B. Mission Level Operations

Mission operations, as we have defined them here, have a much longer history than campaign level operations. Individual aircrews have been briefed on the target to be hit along with suggestions on how to conduct the raid since World War I pilots dropped shells on enemy positions. Given the complexities of today's weapons, we have large planning assistance computer programs such and the Air Force Mission Support System (AFMSS).

1. Mission Planning

Ranging from receipt of the air tasking order (target, objective, weapons load, and time over target) and scheduling the aircrew to providing a tape or mission cartridge for downloading information to the aircraft mission/stores/weapons management system and the weapon itself, the mission planning process is critical to the successful delivery of the weapon.

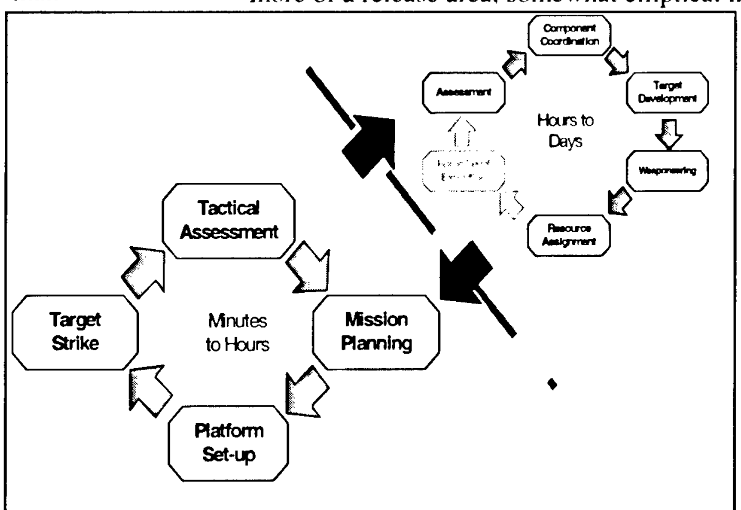


Figure 2 Operations Cycle -- Mission-Campaign Coupling

This task includes analyzing the target and objective area to confirm proper weapon selection and gathering scene perspectives. Likely enemy defenses and threat within the target delivery zone and the route are defined. The actual weapon delivery parameters (range, altitude, direction and angle of attack, speed, weapon setting, etc.) are chosen, and platform maneuvers to attain those delivery parameters are finalized.

Backing up from the delivery point, platform planners determine a safe and efficient route to position the weapon for delivery and still meet time-on-target demands. These include launch, possibly landing and divert locations, air refueling, and consideration of weather conditions and of airspace deconfliction (safe ingress and egress routes that prevent different aircraft from attempting to occupy the same air space at the same time).

With guided weapons, the release point is more of a release area, somewhat elliptical in nature, from which the weapon may still successfully guide to the target. This area is calculated by the weapon planner/mission planning system based on the range, dynamics, and guidance characteristics of the weapon. This is supported in the mission planning software system by a model (3 Degrees of Freedom (DOF) or 6 DOF) of the weapons characteristics. The planning

software can simulate the flight of the weapon and show either the possible impact points from a given release point and conditions or the release area and conditions required to impact a given point with given approach direction and impact angle. Impact velocity which is very important when attacking hardened targets is also calculated.

The entire process is repeated for secondary or tertiary targets, in case the primary target is unreachable or has already been struck.

All of this information (maps, scene perspectives, delivery parameters, etc.) is collectively called a combat mission folder, which aircrews will take with them on the mission. When computer supported mission planning is used, the planning information for each of these targets is prepared and transferred to the aircraft stores management and navigation systems.

On many advanced mission planning computer support systems, planners or aircrews can perform a simulated "fly-by" into and over the target area, with computer visuals, relying on geographic and photographic data allowing construction of a fairly simple, dynamic, polyhedron-based perspective of landmarks and terrain to be encountered on the proposed route.

Our discussion thus far has assumed a ground-based planning cell, with minutes to hours at their disposal to plan a target strike. During divert missions, planners must go through essentially the same process, usually in drastically shortened timeline. Where and how this re-planning should be done, and how long this type of re-planning might take will depend on many different factors, which we will defer until section IV.

2. Platform Set-up

From the time the tasking for a particular mission is received from the campaign headquarters, the support crews for the platform/weapon combination have been busy as well, preparing and loading the weapon system for its designated mission.

The mission planning computer support systems mentioned earlier also support a data transfer device from the computer workstation to the platform/weapon. It will load the planner's decisions onto a read/writeable media that can be carried to the platform and will automatically initialize the aircraft and weapon with way point information, weapons parameters, and the like.

3. Target Strike

The target strike is the instantiation of the entire mission planning effort, both at the campaign and mission operations level.

This task, the culmination of many man-hours of thought and effort, usually is accomplished on the order of seconds.

4. Tactical Assessment

Both the last and the first step of any mission — a tactical assessment of the target area is both an input into the mission planning task and an output, to be fed back into the force-level execution task at the campaign level.

IV. Mission Re-planning

A. General Considerations

We set the stage for our operational consideration of re-planning activities by considering two fundamental questions — what causes mission re-planning, and what impacts the re-planning process?[iii]

B. Mission Re-Planning Causes

The causes of the need to re-plan or re-direct a mission are discovered at various points in the timeline and command level where the re-planning takes place. Not surprisingly, there is a close correlation between the two. While there are many reasons for re-planning, several stand out:

Availability of friendly resources. An increase in capability or availability of bases,

aircraft, or weapons means in turn an increase in available sorties and the possibility of attacking new or multiple

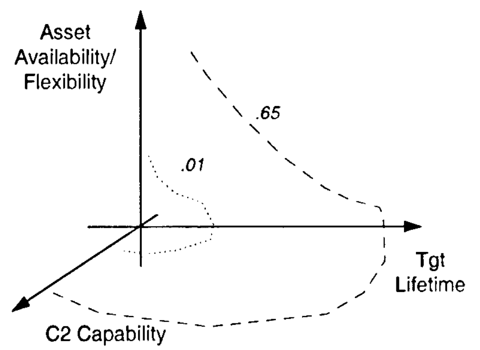


Figure 3 Probability of sortie success based on mission-re-planning considerations. What might iso-probable surfaces look like?

targets that could not safely be attacked at that time with the lesser capability.

New target priorities. New target priorities will be primarily determined based on operational successes or setbacks to date. SEAD missions may take priority over interdiction, if initial intelligence underestimated enemy threats. Unexpected successes also open up the possibility of attacks that even though highly important were thought too dangerous to attack until later.

New priorities will results in different apportionment, as the theater commander shifts his emphasis, and under current operations would take a day or more to fully implement. Re-planning based on new target priorities is currently the purview of the campaign planning staff.

Urgent Close Air Support (CAS) (or other high priority) targets. Every air campaign allocates some portion of its strike forces to close air support, where the exact time or need of the air mission may not be known. These forces are normally allocated to support a particular geographic region. Since aircraft are normally on the ground or possibly even air alert status, mission planning (or re-planning) is done dynamically. In some cases, the general location and type of strike desired is usually known, and the target timeline is relatively long, even for mobile targets. These missions will have been previously allocated for and planned by the campaign planners. In other cases, the location and type of strike required may not be known *a priori*. This is the case of the fleeting target, which we will discuss in much more detail below.

Mission parameter changes. Weather, enemy defensive changes, or lack of accurate target intelligence, etc. characterize the normal divert mission of aircraft. Nearly all missions plan a secondary target site, in case the first is already destroyed or unreachable. Relatively few divert missions are solely targets of opportunity — those that are usually fall into:

Critical emerging threats. Individual targets may emerge during combat that fundamentally impact or even threaten the theater commander's battle plan, like the imminent deployment of weapons of mass destruction. Substantial mission re-planning might be required depending on the target set and its defenses. Again, although the timeline required is shorter than new priorities, it would remain the prerogative of the campaign planner to find the resources needed to attack this target. This scenario is not likely to happen very often. There are few individual targets, that would not have been recognized, of such danger that an entire day's or campaign's operation would be in jeopardy unless they were struck. These would require a significant resource commitment within a very short timeframe.

C. Mission Re-Planning Considerations

There are two primary considerations for mission re-planning feasibility: asset availability/flexibility and target lifetime. Both of these are influenced by the command and control capability that can be brought to bear.

Asset availability/flexibility. This factor primarily combines the number and type of platform/weapon available, the flexibility of that asset to engage different types of targets, and the range (time) needed to engage a given target. Obviously, if a theater has a high number of resources available to it, if the current platform/weapon combination is easily engaged against multiple target types, or the range from a current target to a new one is small, then both the mission and campaign level commanders have considerable latitude in mission re-planning (all other things being equal).

Target lifetime. This is the time that a target's location and defenses can be reliably tracked by the current information resources brought to bear. A tank column in motion with mobile air defense units is representative of a short target lifetime. A power plant with fixed defensive units has a longer lifetime and the time that it is to be neutralized is dependent on its function rather than its availability as a target.

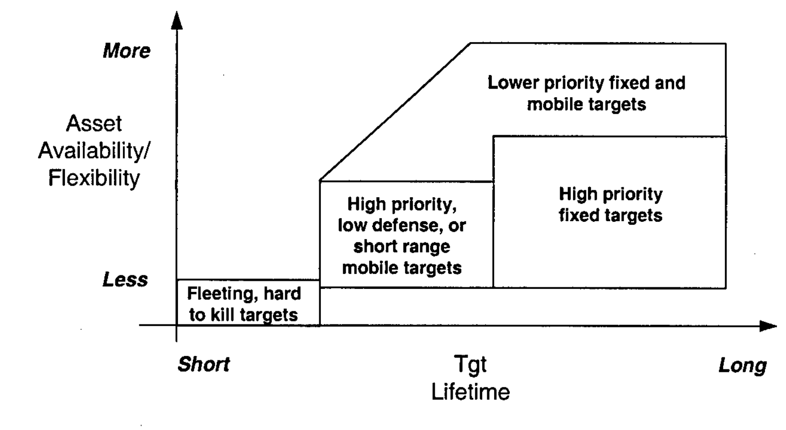


Figure 4 Target Categories

Influencing these considerations are the command and control capability of both sensor to platform/weapon, and within the battle space.[iv] How accurate and timely is the targeting information to the platform crew /weapon? Can highly mobile or fleeting targets be tracked outside their "move-launch-move-hide" window? How much time will be needed for mission re-planning activities, including possible mission rehearsal? How long will mission coordination, including possible air-refueling, SEAD, electronic combat (plus airspace control over all of these) take? Note these questions concern both operational and technology considerations.

A combination of these two critical considerations could lead to a given probability of sortie success. Since command and control capability is not completely independent of target lifetime or asset flexibility, the orthogonal relationship in figure 3 is notional. Nonetheless, a "go/no-go" decision should be made based on the probability of mission success. Where and how this decision should be made, and some technical considerations that will enable the decision-making, is postponed to section VI and VII.

V. Target Types

With the following background in hand, four different types of targets are clear, with different re-planning needs for each of them (see figure 4).

We will deal with the first three in relatively cursory fashion. The driver for new operational and technical considerations lies in the fourth category.

Lower priority targets have varying target lifetimes, but are usually well within today's operational and technical capabilities. Because of their priority, they can be considered later in today's or the next day's planning process. Missions against targets of this nature are routinely re-planned at the campaign level operations (the Air

Operations Center), or as divert missions for close air support.

High priority fixed targets have somewhat less asset flexibility and availability associated with them, because they must be neutralized quickly. Because air assets are either involved in planning for or dedicated to other operations, the mission re-planner will have less flexibility for dealing with them. Mission re-planning will initiate at campaign level, with close coordination with mission level crews once resources are identified. As with the above, no significant operational or technical changes are needed.

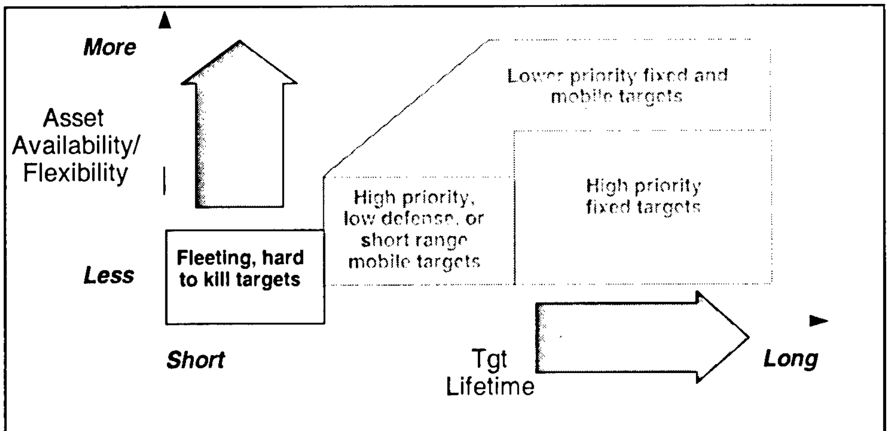


Figure 5 Considerations for killing fleeting target sets -- two degrees of freedom are possible

- Air To Surface Weapons
  - Unpowered
    - Unguided
    - Guided
      - Inertial Only
      - GPS Aided
      - Man-in-the-loop
      - Autonomous Seeker
      - Cued
  - Powered
    - Guided
      - Inertial Only
      - GPS Aided
      - Man-In-The-Loop
      - Autonomous Seeker
      - Cued

Figure 6, Families of weapons

High priority mobile targets that can move easily, but must stop and set up to be dangerous, represent the class that has the best improvement-priority product. Technology can improve the probability of hitting these targets before they can hide or be lost in a cluttered environment. The location of such a target must be communicated through the observing source, various command information channels, to the flight control for the designated strike aircraft and to that aircraft itself. In the case of a "smart" weapon the target parameters must also be communicated to the weapon's guidance and control system.

VI. Weapon Characteristics

Today's "smart" weapons are a far cry from the "dumb bombs" from years past. The weapons of the past acted like chunks of iron and simply fell toward the target. Today weapons take on characteristics more like piloted aircraft. The weapons fall into families that have varying degrees of aircraft-like characteristics. The first delineation is direct attack or stand off. In direct attack, the pilot of the delivery aircraft maintains visual contact with the target through launch. In stand off attack, the pilot launches the weapon and then can turn to avoid the immediate target area.

A. Air-to-Surface Weapon families

When considering the different classes of weapons, it is common to consider first the

separation of those that are powered and those that simply fall or glide toward the target. It makes more sense first to divide weapons into categories based on whether they are guided or not and then on the type of guidance. Whether they are powered or not does affect range, but a similarly guided unpowered weapon can perform much like a powered cousin in short ranges. Next, if the weapon is guided, we consider those that have seekers and those that have some other method for finding the target.

Without a terminal seeker, a weapon must rely on some knowledge of its location. We will assume that a data link or some other man-in-the-loop guidance scheme is not feasible without a terminal seeker, so the weapon must determine its location internally. Two common methods exist.

The first is inertial guidance based on position, angle, and rate information transferred from the launch aircraft to the weapon prior to release. For inertial guidance to work, the weapon must also know the inertial space location of the target. The target location in the coordinate system agreed to by the launch aircraft and the weapon is one of the primary parameters loaded from the mission planning system.

Inertial guidance has great benefits when first considered. It is relatively simple, costs have been falling, and it does nothing to alert the enemy of its presence. Unfortunately inertial instruments drift. The longer that a weapon flies from a known location, the less precise its estimate of its location is. This translates to a larger miss distance of the weapon impact. This produces two problems. With relatively small weapons and hardened targets an unacceptable miss distance can cause the strike to be ineffective. The second problem is that of collateral damage. High value targets are often placed adjacent to civilian or religious facilities. Accidentally hitting such a location in the era of CNN can cause loss of will on allied sides, as well as strengthening the resolve of the enemy.

Second, a method that would reset the inertial error before it becomes unacceptable, would keep miss distances within the required values. The Global Positioning System (GPS) performs this function well. A receiver on the weapon constantly updates the inertial system's estimate of position. Since the inertial system can maintain position accurately for short periods of time, the weapon can continue to guide during GPS signal dropout.

Those weapons that have terminal seekers fly out to the target vicinity using inertial guidance and then attempt to remove aim point error by allowing a terminal seeker to provide final guidance commands to hit the target. Weapons with terminal seekers may be totally autonomous, or guided by some external cueing device or via a data link from a person that has information from the trajectory of the weapon.

Autonomous seekers perform some form of target recognition or image analysis to detect, identify, and guide to the target. The mission planning information necessary for this type of seeker is quite complex and involves building models of the target and being able to recognize the target in different weather, at different approach angles, with a portion of the target destroyed, and with smoke. Re-planning of this type weapon is the most difficult technically.

Man-in-the-loop (MIL) seekers, have some form of data link to allow an operator to view information such as a television or infrared video stream from the weapon's seeker. The operator must simply fly the weapon to the point on the target previously designated. Mission planning for this type of weapon consists of inertial information to provide flight path and information such as photographs that will assist the operator in recognizing the target.

Cued weapons have a seeker that responds to targeting information such as a coded laser spot on the aim point. This is a variation of the MIL seeker but in the conventional MIL

system, the weapon operator is located in the launch aircraft or another aircraft in the flight. In a cued system the person controlling the terminal approach of the weapon (target designator) may be anywhere within visual range of the target. Mission planning for cued systems involves providing targeting information to the designator as well as ensuring the proper inertial flight of the weapon to a point where cued guidance is possible.

B. Route

The route from takeoff to weapon impact for a stand off weapon is divided into distinct and separate activities. The carrier aircraft transports the weapon to a launch point within the weapon's range of the target. This launch point does not have to be exactly precise; therefore, a region or launch "basket" is defined. The target location, weapon's range, and the flight dynamics of the weapon define the size and position of the launch basket. A truly stand off weapon will navigate in an aircraft fashion using way points and route segments to avoid threats and obstructions to a terminal transition point or terminal basket. Each of these route segments must be flown to avoid most if not all of the danger from ground based anti-aircraft weapons. The terminal basket, in the vicinity of the target, is much smaller and the exact location of the weapon is much more critical than the weapon launch basket. During the terminal phase, the weapon can perform high G maneuvers to approach the target at the exact aim point and at an effective impact angle. It is the purpose of mission planning to build routes that will minimize this danger.

VII. Re-planning Requirements

Since re-planning before weapon take off can be worked as a modification of the normal planning process, we will only discuss in-route re-planning. Each type of weapon presents a different problem and opportunity in re-planning. A direct attack weapon with no guidance capability is planned and re-planned just as the carrier aircraft, because there are no other methods for affecting the performance of the weapon other than through ejection/launch conditions.

In order to re-target an inertial guided weapons in route, the new target's coordinates in inertial space must be communicated to the navigation and guidance systems both on the launch aircraft and the weapon. This requires some data path from the analysis center, surveillance aircraft, or other source with precise knowledge of the precise location of the target and aim point. The position information must be transmitted to the launch aircraft, assuming that the target location system is not on the launch aircraft, processed, and then communicated to the weapon. This also requires that the aircraft can transmit location data to the weapon. Therefore, an inertially guided weapon that is programmed on the ground and then carried on an older aircraft without a weapons bus cannot be re-targeted (re-planned) in route.

Re-targeting of a GPS-aided, inertially guided weapon has essentially the same requirements to transmit target position information from the planner to the weapon.

Weapons with an operator in the guidance loop must be given the approximate position where terminal (MIL) guidance is to begin so that when the seeker is turned on, the target is in the weapons field of view. The operator who guides the weapon during the terminal phase to target impact must be given information (pictures, maps, and/or diagrams) to find, recognize, and positively identify the target and to select and track the aim point.

Re-targeting for an autonomously guided weapon represents the greatest challenge. The initial targeting involved building models of the target, determining feature vectors, analyzing the effect of approach angle on the appearance of target, and many other operations. To retarget an autonomous

weapon, all of these steps are necessary along with the necessity to transmit target recognition information to the weapon. This requires significantly greater bandwidth of data communication between the planner and the weapon.

The re-targeting of cued weapons is similar to that of the man-in-the-loop weapons. Position of the release point from the aircraft or the point where the weapon goes into terminal mode must be transmitted to the aircraft and weapon. Also, the exact target information and aim point has to be transmitted to the operator of the illuminator or cueing device.

A. Information flow/technical requirements:

Each of the above methods that require transmission of targeting data to the aircraft or weapon introduce required analysis of bandwidth of targeting information, communications capability and bandwidth to the weapon, ability to adapt to changing requirements, range of possible communications, etc.[v] The result of this analysis for each weapon will create individual specifications for the communications scheme.

B. Operational requirements:

The operational requirements may represent a more difficult decision than the technical. This analysis must determine: Who should decide when and how to re-plan and attack? What information does the shooter/decision-maker need? What information does he definitely not need? These and other questions must be addressed in concert with the technical requirements.

VIII. Implications for Unmanned Tactical Aircraft (UTA)

UTAs can contribute to the solution space – they can help either axis to increase our effectiveness. They can increase the target visibility lifetime axis by loitering in areas of prospective target availability to be on station to observe a target that becomes visible. Also they can increase the weapon availability axis by carrying weapons or designators so that once a target is detected, they can participate in its neutralization.

Information transfer of targeting information is similar for UTAs to that for weapons. The UTA will, however, generally also provide intelligence information from their operational area to the various command centers.

IX. Philosophical Considerations

The idea of a pilot or flight leader redirecting a weapon strike generally goes against the current 'centralized planning, decentralized execution' much prized by today's planners. This is in reaction to past campaigns where much of the massing, surprise, flexibility, and economy of force that air power brings to a campaign was lost when that air power was parceled piecemeal out to ground forces.

The operational considerations listed above, in particular with delegation of 'clear to shoot' authority, and relaxation of rules of engagement (ROE), will be a long time coming. In fact, the technology will almost certainly have to be present and the operators thoroughly comfortable with it before any movement downward in clearance to release. Ironically, that same technology that brings a flow of information into the shooter, and that should bring greater freedom to him, may also be feared by him. The same communications suite that carries vital targeting information to him could just as

easily transmit data back to the command center and mean that a flag officer could read his HUD and direct him when and how to engage a target.

X. Conclusion

Technical solutions exist to the problem of redirecting weapons to new targets if those new targets can be located and the information communicated to the attacking aircraft. Each of the types of guided weapons discussed has a mechanism for target position/recognition information to be stored and used. For redirection to be accomplished, some form of communications channel must be established from the target selecting person to the aircraft, weapon, and, if applicable, the designator. With some weapon systems, the necessary communications channels only need minor modifications, with others new equipment and significant changes are necessary to the aircraft and weapon. These channels can be established with today's technology, but fundamental changes are necessary to the planning doctrine.

XI. References

[i] Joint Publication 3-56.1, "*Command and Control for Joint Air Operations*", 11 November 1994

[ii] United States Air Force Air and Ground Operations School (AGOS) Computer Based Training Course, "*Joint Air Operations Center Operations*", December 1996

[iii] P. Sergent 3 Feb 97 working level memo to AGARD/MSP WG-03 members

[iv] Advanced Battlespace Information Study (ABIS) Task Force Report, Vol. I - VII, September 1996

[v] United States Air Force Scientific Advisory Board (USAF SAB), New World Vistas, December 1996

Autonomous Navigation and Control Functions of the CL-327 VTOL UAV

M. Pelletier, A. Sakamoto, C. Tessier, G. Saintonge
Bombardier Inc., Defence Systems Division
10,000 Cargo Rd A-4
Mirabel, Quebec J7N 1H3, Canada

1. SUMMARY

The CL-327 vertical take-off and landing unmanned air vehicle has a payload carrying capability of 100 kg and an on-station endurance of 4.75 hours at 100 km (based on 50 kg payload). Although similar to that of the CL-227, the pitch, roll, yaw and height autopilots have been modified and improved to account for the capabilities and dynamics of the CL-327. The advanced guidance, navigation and control functions include GPS/DGPS-aided flight, waypoint guidance, automatic (vertical) take-off and landing as well as autonomous flight without the intervention from the surface element. Because of these and other advanced features, the CL-327 is the world's most advanced VTOL UAV in production today.

2. INTRODUCTION

Today's peacekeeping and warfighting challenges require mobility, flexibility and up to date information. Systems that permit immediate decision making by the on-scene commander will make the difference in regional conflicts and contingency operations. Early use of Unmanned Air Vehicles (UAV) internationally has confirmed their value in filling this role. The requirement to deliver information to the intended users in a timely manner necessitates a UAV system which carefully integrates the air vehicle, the sensors, the image processing and the armed forces command, control, communication and information (C^3I) architecture into a coherent whole.

The CL-327 system comprises an enhanced version of the Bombardier/Canadair CL-227 Vertical Take-Off and Landing (VTOL) Sentinel air vehicle [1], and a Macdonald Dettwiler and Associates (MDA) UAV Control Station (UCS) and image exploitation system. The airborne elements of the system include the Air Vehicle (AV), ELTA's digital Air Data Terminal (ADT), and high performance sensors including color daylight TV, spotter camera, Forward Looking Infrared (FLIR) and laser range finder. These airborne elements offer superior capabilities for reconnaissance, surveillance and target acquisition in all situations. The ground elements include the UCS, the Ground Data Terminal (GDT), and the launch and recovery equipment. The UCS capabilities include UAV flight planning, control and monitoring, sensor control, image correction and analysis, real-time data capture, and displaying of graphical and geographical information.

The CL-327 has an endurance of 6.25 hours (compared to 2.5 hours for the CL-227), a ceiling altitude of 5500 m (compared to 3000 m), and a payload carrying capability of 100 kg (compared to 25 kg). The CL-327 air vehicle VTOL characteristics allow for launches and recoveries from confined areas typically 10 m x 10 m enabling formations to minimize the likelihood of detection. Its hovering capability permits continuous surveillance of a single point in cluttered areas such as cities.

The paper first describes the general characteristics and specifications of the CL-327. The flight performance of the AV is then presented, followed by the guidance, navigation and control functions. These include GPS/DGPS-aided and inertial navigation, automatic take-off and landing, waypoint guidance as well as autonomous flight. Flight testing is discussed next in Section 7. The paper concludes by presenting some future developments of the CL-327 air vehicle.

3. THE CL-327 AIR VEHICLE

3.1 General Description

The air vehicle is a rotary wing type UAV using counter rotating rotors for propulsion. As illustrated in Figure 3-1, six 203 cm long ARDCO rotor blades tapered with 12° twist provide lift and control to the AV. They are made of composite material with protective tape against rain erosion on the leading edge. They are configured with a modified Gottingen airfoil which provides a high lift-to-drag ratio.

The rotor blades operate at a maximum speed of 750 rpm. Rotor speed is reduced to as low as 585 rpm at engine idle with a minimum operating speed of 650 rpm. The lower operating speed maximizes fuel efficiency in loiter conditions and during flight in light and medium weight conditions. The rotor blades are installed in a few seconds without any tools, as the rotor blade shanks are secured in the blade housing using a pin and spring clip.

Paper presented at the AGARD MSP Symposium on "System Design Considerations for Unmanned Tactical Aircraft (UTA)", held in Athens, Greece, 7-9 October 1997, and published in CP-594.

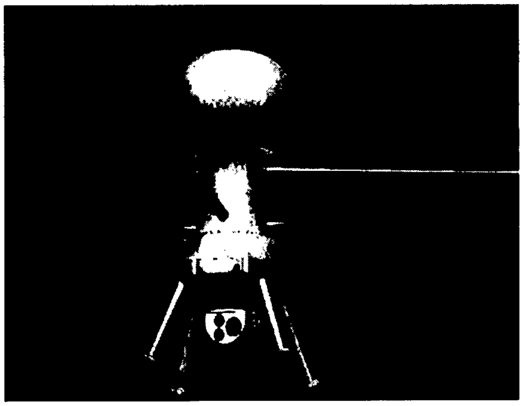


Figure 3-1: The CL-327 VTOL UAV

The CL-327 can operate in ambient temperatures of -40°C to +57°C. It has inherent characteristics that minimize Infrared (IR), acoustic and radar signatures. Figure 3-2 presents a cut-away view of the AV that shows the major equipment excluding the blades.

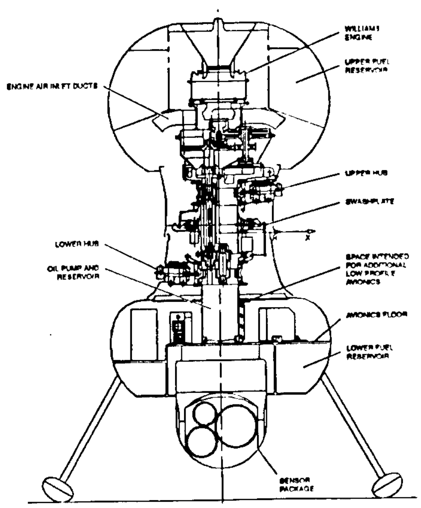


Figure 3-2: CL-327 Cutaway View

3.2 Engine and Transmission

The powerhead consists of a WTS 117-5 single turbo shaft turbine (100 HP flat rated) utilizing a single stage radial flow compressor, an effusion-cooled annular combustion chamber and a single radial inflow turbine. The engine operates on heavy fuel (e.g.: diesel, JP-4, JP-5, JP-8, JET A) without requiring any adjustments or purging. Fuel is supplied from an externally mounted fuel pump which is controlled by the Integrated Avionics Computer. The upper fuel reservoir (130 l capacity) is located around the engine and is made of carbon fibre. It includes baffle plates to reduce sloshing of fuel and it is vented to atmosphere. It is linked to the lower fuel reservoir which can contain up to 50 l of fuel. The upper fuel reservoir attaches directly to the engine gearbox and includes fuel level sensors. In order to transmit power from the engine to the two rotor hubs, the powerhead is mated to a two stage reduction gearbox utilizing spur gears.

3.3 Propeller Module

The propeller module is located in the central part of the vehicle and houses all mechanical elements required for AV propulsion in terms of thrust and control moments. The main structural element is an aluminium center tube. Located at each end are the upper and lower rotor hub assemblies with blade retention and blade feathering mechanism. Located on a slider between the two hubs is the swashplate assembly. Three linear electrical actuators are mounted equally spaced around the base of the center tube attached to the swashplate. Pitch links from the swashplate are attached to the blade retention assembly. Equal extension of the linear actuators provides control of the collective blade pitch angle, while differential extension provides cyclic angle control for pitching and rolling motions. An additional three actuators mounted on the swashplate provide differential collective between the two rotors for yaw control. By changing the distance between the two rotating rings to which the upper and lower hub pitch link attach, the collective angle between the upper and lower rotor blades is changed thus inducing different drag-based torque reactions leading to a net yaw moment.

3.4 Lower Structure

The lower structure is made of composite materials and houses all avionics equipment (100 l capacity), the ADT, the fuel distribution system, landing struts, as well as the Sensor Package (90 l capacity).

The main avionics equipment of the vehicle is the Integrated Avionics Computer (IAC). It consists of two i960 processors: the Flight Control Processor (FCP) and the Navigation Control Processor (NCP). It also includes an Inertial Measurement Unit (IMU) using fibre-optic gyros, a GPS receiver, an Engine Controller Unit, a Barometric Altitude Reference Unit (BARU) and a Power Supply Unit (PSU). The IAC provides for multi-mode navigation, guidance, vehicle control and stabilization, altitude computations, sensor control, engine control and built-in tests.

The landing struts allow safe and damage-free landings for maximal velocities of 2.5 m/s vertically and 0.5 m/s horizontally, and roll angles of up 20°. They are made of composite materials and are interchangeable. They are equipped with proximity sensors to determine the moment the AV becomes airborne and when it touches the ground.

4. FLIGHT PERFORMANCE

4.1 Aircraft Operating Envelope

The operating envelope for the CL-327 AV is shown in Figure 4-1. The International Standard Atmosphere (ISA) day flight envelope shows that the AV with a maximum take-off mass of 350 kg has a hover capability up to a density altitude of 2740 m, an operating ceiling of 5500 m, and can achieve a maximum dash true airspeed of 85 kts (157 km/h). Table 1 summarizes the main characteristics of the CL-327.

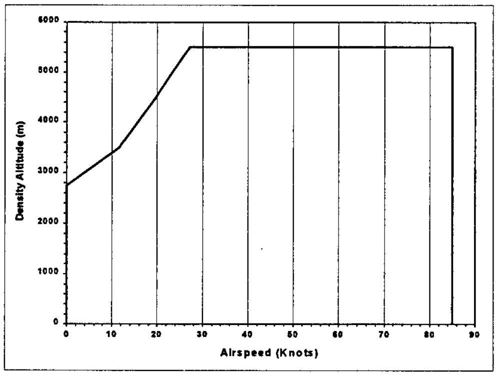


FIGURE 4-1: CL-327 Operating Envelope, ISA day (Preliminary data)

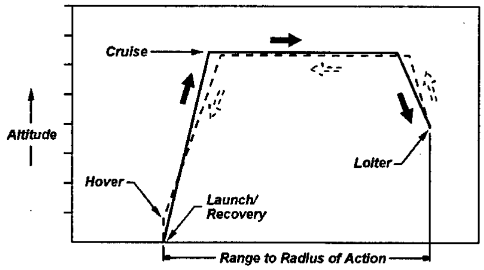
4.2 On-Station Endurance

The on-station endurance of the CL-327 is based on the mission profile of Figure 4-2. The AV operation during each mission leg is optimized in terms of airspeed and rotor speed, so as to maximize the time on station at a given range.

Rate of climb	7.6 m/s
Service ceiling	5500 m ASL
Maximum speed	85 kts (157 km/h)
Minimum speed	Hover
Endurance	6.25 hrs (4.75 hrs at 100 km with 50 kg payload)
Radius of action	100 km (200 km option)
Max. launch weight	350 kg
Max. payload weight	100 kg

Table 1: CL-327 Preliminary Specifications

The vehicle take-off mass is set to 350 kg, including a fuel load of 150 kg and a payload mass of 50 kg which represents the weight of a typical payload. A pre-launch fuel allocation of 2 kg was used, which corresponds to a 5 minutes warm-up period plus take-off fuel. Fuel reserves are based on 30 minutes hover 50 m above the recovery density altitude. The 30 minutes reserve can easily be extended if maximum endurance loiter is used instead. Figure 4-3 provides the on-station endurance as a function of range for take-off at sea level, a cruise altitude of 3000 m, and loiter altitudes of 2000 and 3000 m. These results show that, for a 100 km range mission, the maximum on-station endurance is 4.75 hours.



MISSION PROFILE	*RPM*
Launch at 350 kg at indicated density altitude	750
Maximuim ROC climb to cruise altitude	750
Best cruise to radius of action	750
Descent to loiter altitude	650
Loiter on station at maximuim endurance speed	650
Maximum ROC climb to cruise altitude	750
Best cruise back to launch point	650
Descent to recovery altitude + 50m	650
Hover at recovery altitude + 50m for 30 min	650
Vertical landing to recovery altitude	650

Figure 4-2: Typical Mission Profile

The long endurance of the AV is achieved by operating the rotor blades at two different rotational speeds: 750 rpm for full power and 650 rpm for moderate power.

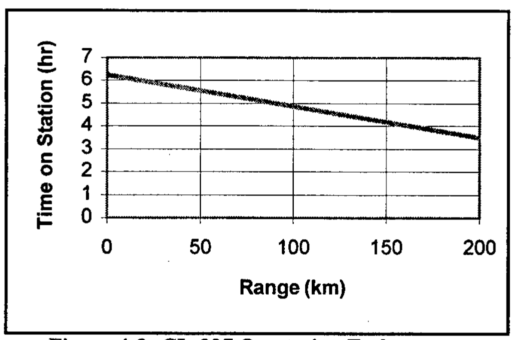


Figure 4-3: CL-327 On-station Endurance (Preliminary data)

4.3 Operation in Icing/Rain Conditions

The CL-327 has inherent characteristics which make it less susceptible to ice formation during flight and, therefore, does not have a built-in de-icing system. Operational deployment of the AV under severe conditions at sea (North Atlantic, North Sea) has been demonstrated without the need for de-icing capability while on the ground. The AV structure will withstand 6 mm of ice and 13 mm of snow, when fitted with protective covers. Accumulated ice and snow must be

removed manually prior to flight. The actuation mechanism for control of the blades are covered with "spinners" which effectively prevent ingress of ice and snow to the critical moving parts. Because of the leading edge protective tape, the CL-327 rotor blades can operate in continuous rain of up to 1.5 cm/hr.

5. GUIDANCE, NAVIGATION AND CONTROL FUNCTIONS

5.1 Description

The Guidance, Navigation and Control (GNC) functions of the CL-327 are depicted in Figure 5-1. The Navigation function provides estimates of the AV translational and angular position and velocity to both the Guidance and Flight Control functions. The Guidance function elaborates high-level commands to make the AV follow a flight path. These commands are automatically converted into low-level commands which are then implemented by the Flight Control System (FCS), responsible for stabilizing the AV in flight. Both the Guidance and Control functions are implemented in the FCP, which also takes care of communication, mission control and monitoring, envelope protection, system management, engine control and error management.

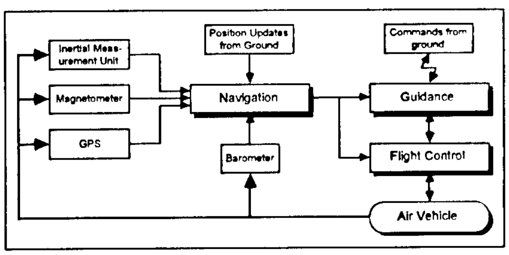


Figure 5-1: High-Level Architecture of the Guidance, Navigation and Control Functions

The combination of the GNC functions with different communication modes give rise to advanced capabilities such as automatic and autonomous flight as well as automatic take-off and landing which will be detailed in the following sections.

5.2 Flight Control Functions

The FCS structure is illustrated in Figure 5-2. The Guidance commands for height, yaw and horizontal (ground) velocity (i.e. tilt and tilt heading) are transmitted to the FCS. These commands are first converted into equivalent roll, pitch and yaw commands for the corresponding roll, pitch and yaw autopilots. Motion feedback is provided by the Navigation function. The height, roll and pitch autopilots are mixed together and act on the AV swashplate which then sets the average collective and cyclic angles of the two rotors. The yaw is controlled directly by changing the differential collective angle. In order to maintain the same average collective angle, the Collective Mix must compensate any increase (decrease) in differental collective by decreasing (increasing) the collective.

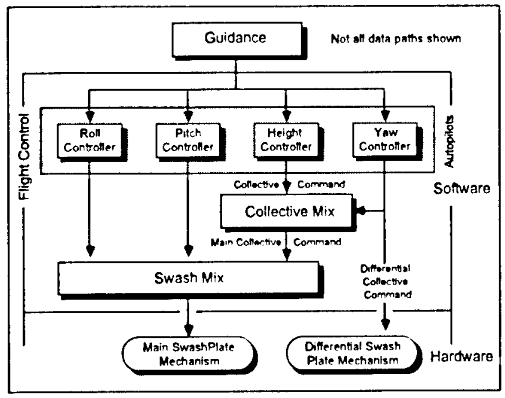


Figure 5-2: High-Level Architecture of the Flight Control System

5.2.1 Flight Control Design

The CL-327 is symmetrical about the central axis and can tilt in any direction of flight. Operating requirements dictated the control strategy in the design of the CL-327 FCS. It consists of four independent digital control loops, namely pitch, roll, height and yaw, and was designed from a linearized model of the vehicle's dynamics. Because of the inherent instability of the airframe, the dynamic time response is completely dominated by the FCS rather than by aerodynamics. Figure 5-3 shows the dynamic time response around the pitch axis to a square pulse command.

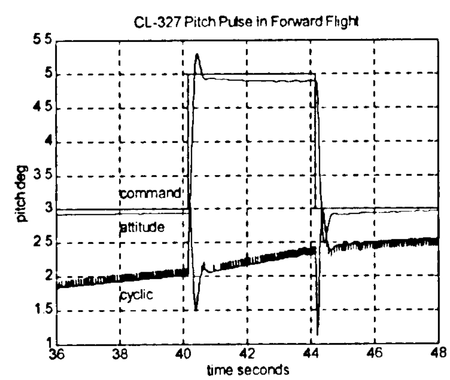


Figure 5-3: CL-327 Pulse Response (Theoretical)

5.2.2 Manoeuvre Performance

The CL-327 is not designed for manoeuvre performance. The only benefit of manoeuvre performance is to reduce turn radius for more flexibility in target tracking. With the CL-327, a payload can easily provide this flexibility. The air vehicle only requires sufficient cyclic to enable changes in flight state and direction. Thus in the operational version of the CL-327 all the manoeuvre limitations will be built into the autopilot. In order to establish these limitations, flight tests will be performed to confirm the trim cyclic requirements, and determine the dynamic cyclic requirements during manoeuvres. Figure 5.4 shows the theoretical trim cyclic plotted against airspeed for different ambient conditions.

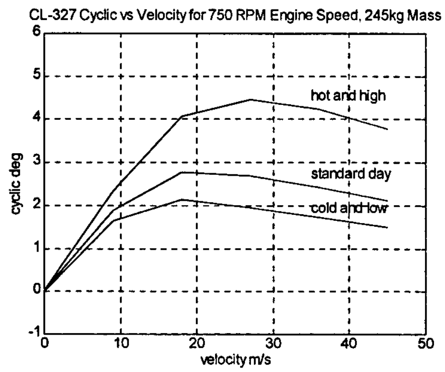


Figure 5-4: CL-327 Cyclic vs Velocity for 750 RPM Conditions (Theoretical)

5.2.3 Pitch and Roll Design

The response of the CL-327 pitch and roll controllers was designed to be similar to the CL-227. An adaptive gain ensures that the response remains the same under all ambient, mass, and engine speed conditions. The basic closed loop design criteria were that the overshoot be less than 3db, and the bandwidth be at least 12rad/sec. The open-loop response criteria required at least 4dB gain and 20deg phase margin. The lower-than-normal specifications in phase and gain margins are permitted as the CL-327 is not a manned aircraft. They are improved, however, over the CL-227, mainly due to reduced forward and reverse path delays as the IAC is approximately 6 times faster than the original Canadair Inertial Navigation Processor (INP). A typical closed-loop response is illustrated in Figure 5-5.

5.2.4 Yaw Control Design

The response of the CL-327 yaw was also designed to be similar to the CL-227, however the basic control format was modified to take into account the replacement of the clutches by a differential collective system. An adaptive gain was required to adjust for changes in inertia, collective and engine speed. The design will be validated during in-house rig testing prior to the first flight at the tether facility.

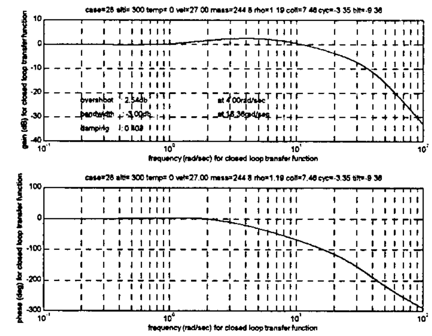


Figure 5-5: CL-327 Closed-Loop Response (Theoretical)

5.2.5 Height Control Design

The height autopilot was re-designed for the CL-327. Previously height control for the CL-227 had been limited due to the complementary filter relying heavily on the barometric pressure due to inaccuracies in the z-acceleration sensor. This created control problems when the local pressure around the AV was no longer representative of the actual altitude. The worst occurrences were during the landing phase (ground effect), and during low airspeed descents (vortex ring effect). However, with the NCP, the accuracy and reliability of the measured height signals has been significantly improved. Consequently minor changes in pressure will now no longer affect the control of the AV in height. The climb and descent rates, previously fixed at -1.5 m/s and +2.0 m/s, will now be variable between -5 m/s and +7.6 m/s. The maximum allowable descent rate will be limited depending on the airspeed to avoid a real vortex ring condition. The ability to specify the climb and descent rates will also allow the automatic navigation to perform line-of-sight waypoint navigation in the vertical axis.

5.2.6 Other Design Modifications

Several other control design modifications were implemented during the upgrade from the CL-227 to the CL-327, as follows:

- The delta rpm monitoring and excursion detection modes were removed.
- The landing detection scheme was simplified as landing leg sensors were included in the design.
- The Exhaust Gas Temperature (EGT) limiter was redesigned for the new engine and transmission.
- A new, more flexible swashmix design was implemented.

- A ground velocity controller mode was added, controlled by the joystick or through the automatic navigation.

5.3 Automatic Guidance Function

The Guidance function of the CL-327 allows the AV to follow a flight path which is either pre-defined (automatic guidance) or controlled manually by an operator from the ground using a joystick (manual guidance). In manual guidance, either the AV tilt or air velocity can be controlled. In automatic guidance, the flight path is defined with a series of waypoints in between which the AV will follow straight lines. Each of these waypoints (maximum 255) is defined by a series of parameters including:

- `latitude`, `longitude` and `altitude`;
- `speed` (in between two waypoints);
- `stop_at_waypt` (TRUE: stop there until further notice), FALSE: continue to next waypoint);
- `mission_ends_at` (TRUE: end mission, FALSE: continue to next waypoint).

The structure of the waypoint definition allows for a great flexibility in the elaboration of mission plans. For instance, it is possible at any time during a mission to modify any of the waypoints parameters, for one or several waypoints. The editing/definition of the mission plan is normally performed by an operator at the UCS using a graphical interface. The modified plan is first validated and then uplinked to the AV.

5.4 Navigation Function

The Navigation function is provided by the NCP which receives data from the different sensors. The Integrated Navigation Filter (INF) automatically selects the best navigation mode based on sensor availability and uses Kalman Filtering to compute accurate position/velocity estimates. The INF also performs in-flight calibration of the gyroscopes and accelerometers.

5.4.1 Navigation Modes

For horizontal navigation, in order of priority, the following (main) modes are used: DGPS-aided, GPS aided, GDT-aided, and dead reckoning. In GDT-aided mode, the INF is driven with position fixes computed from the UCS based on GDT air vehicle tracking data. No velocity updates are used in this case. In dead reckoning mode, the IMU is used to compute the estimates based on the aerodynamic characteristics of the AV.

For vertical navigation, the 3-D DGPS/GPS position and velocity updates are integrated with the BARU-derived altitude and inertial measurements (integrated mode). When 3-D DGPS/GPS data are not available, the BARU and IMU measurements are used.

5.4.2 Airspeed Estimate

Since the CL-327 is symmetrical, there is no nose on which to mount a pitot tube. Furthermore, the yaw system is used to point the ADT back to the GDT so there is no simple way of determining airspeed. Because of this, the Navigation Function includes a Wind Estimator. An on-board drag curve is used, based on ambient and AV conditions, to determine the theoretical airspeed. This airspeed is then displayed in the UCS for the operator. The drag curve is determined experimentally by performing steady state runs at different tilt angles within a localised area to minimise wind variations. With an accurate ground speed measurement, the wind speed can be estimated by taking the difference in ground speeds of opposing runs at the same tilt angle. By performing these tests several times a solid database can be built that accurately represents the airspeed of the CL-327, which can then be implemented in the on-board FCP.

In dead-reckoning, the wind estimator is frozen, so the accuracy of the computed position depends on the steadiness of the wind.

5.5 Communication Modes and Autonomous Flight

The CL-327 AV has the ability to automatically carry out a pre-programmed mission with or without intervention from the surface (ground or ship) element. When the uplink is intentionally interrupted, the AV is said to be in autonomous flight mode. In this case, the AV relies solely on the inputs from airborne instruments as depicted in Figure 5-6. Autonomous flight mode is achieved by combining automatic guidance with either the silent or downlink-only communication modes. The main communication modes and features of the CL-327 are the following:

- Normal mode: Bi-directional communications between the AV and surface element.
- Silent mode: Uplink and downlink are intentionally interrupted. The AV follows a pre-defined flight path.
- Downlink only mode: Uplink only is intentionally interrupted. This allows the AV to send imagery data to the surface element upon arrival at the mission area.
- Unscheduled mission plan update: In autonomous flight mode, the AV is constantly on the look-out for an unscheduled re-establishment of the link by the surface element or from another Operational (OP) Section.
- Handover mode: During flight, a request is sent to the AV to hand over the control to a different

UCS and/or GDT.

- Inter AV communication: The AV always listens to possible messages from another AV (see Section 8.2 on Multiple Air Vehicle Operation).

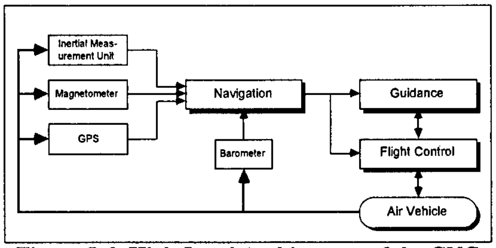


Figure 5-6: High-Level Architecture of the GNC Function (Autonomous mode)

Table 2 presents a summary of the CL-327 main navigation, guidance, and communication modes.

5.6 Reversionary Recovery Mode

As a safety feature, the AV reverts to a reversionary operation mode if loss of link has occurred as depicted in Figure 5-7. In this mode, the AV climbs vertically at a preset altitude of typically 1500 m Above Ground Level (AGL). The AV will keep this position for 10 minutes, then proceed to a preset reversionary waypoint, and maintain it until the fuel remaining is only sufficient to safely land at which point the AV initiates a vertical constant rate of descent until it reaches the ground. From the moment the AV enters reversionary mode until it initiates the final descent, the AV continuously attempts to re-establish the RF link by yawing at a controlled rate.

Navigation (Horizontal)	DGPS / GPS aided
	GDT aided
	Dead Reckoning
Navigation (vertical)	BARU-Inertial
	Integrated (GPS-BARU-Inertial)
Guidance	Automatic (waypoints)
	Manual (tilt or velocity)
Communication	Normal (bi-directional)
	Silent
	Downlink only

Table 2: Summary of CL-327 Modes

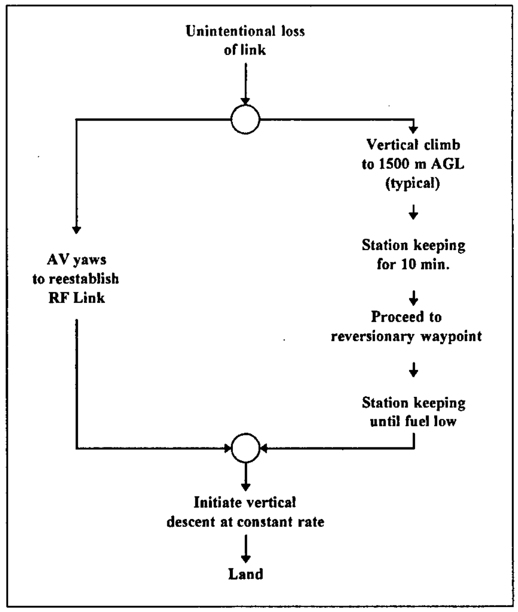


Figure 5-7: Reversionary Mode

6. TAKE-OFF AND LANDING

6.1 Take-Off and Landing Performance

As a Vertical Take-off and Landing (VTOL) AV the CL-327 launch and recovery performance is similar to that of helicopters. The Operational VTOL capability requires the AV to achieve a vertical acceleration of 2 m/s^2 and Rate Of Climb (ROC) of 2.5 m/s in order to climb vertically and maintain hover Out of Ground Effect (OGE). In the case of the CL-327, hovering OGE requires more thrust than actual take-off acceleration because the proximity of the rotors to the ground (about 1 m) creates a ground effect which provides supplemental thrust. Therefore, the take-off performance envelope is based on hover OGE. The maximum take-off altitude is presented in Figure 6-1 as a function of gross take-off mass and ambient temperature. This performance clearly indicates that the AV is capable of launch at nominal take-off mass of 300 kg at density altitudes greater than 4000 m under ISA conditions. With a maximum mass of 340 kg, the AV can take-off at density altitudes of 2740 m. Ensuring that the AV can maintain hover OGE results in the vehicle having the capability of controlled vertical take-off and landing under the same conditions.

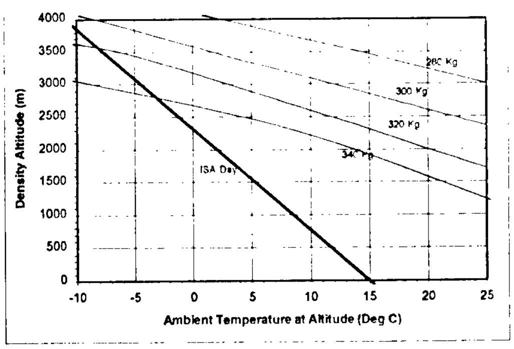


Figure 6-1: CL-327 Take-off and Landing Envelope (Preliminary)

The inherent VTOL characteristics of the CL-327 AV allows for operation in very confined areas from unimproved (grass/dirt) surfaces. Typically, a clearance of 10×10 m^2 is sufficient to carry out launches and recoveries with cross winds up to 30 knots. The dimension of the area required is based on the rotor diameter (4 m) and cross winds. Within this area, the AV can be launched and recovered either in automatic or manual mode.

6.2 Take-Off and Landing Operation

Automatic launch and recoveries are performed by having the UCS and/or AV perform the AV operator actions as an "Automatic Operator" (AO). For automatic launch, the AO sends the "Launch" command and automatically steers the AV toward the first mission waypoint. For automatic recovery, the AO steers the AV above the touch down point during descent. For safety reasons, the operator can intervene at any time by commanding a wave-off and sending the AV at a predetermined waypoint away from any hazardous areas. The system can also be set to allow the operator to manually initiate the last descent phase of recovery.

6.2.1 Automatic Launch

When the operator commands automatic launch, the AV climbs out vertically until it clears any nearby obstacles (e.g. trees, buildings). Using the appropriate navigation mode and automatic guidance, it then steers itself to the first mission waypoint. The VTOL characteristics of the CL-327 AV allows for very high flexibility in planning the launch profile. A typical profile is depicted in Figure 6-2.

6.2.2 Automatic Recovery

In automatic recovery, the AV starts its approach after successfully achieving the last mission waypoint. At this point, the UCS uplinks the ground DGPS correction data as well as barometric reference data to calibrate the BARU. The AV then follows a pre-planned approach profile until it reaches a hovering position above the touch down point. The AV then proceeds with the final descent. A typical profile is depicted in Figure 6-3.

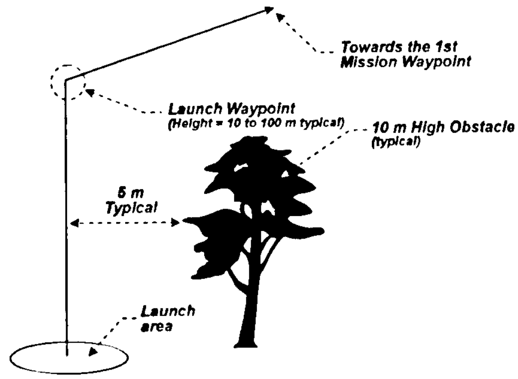


Figure 6-2: Typical Launch Profile

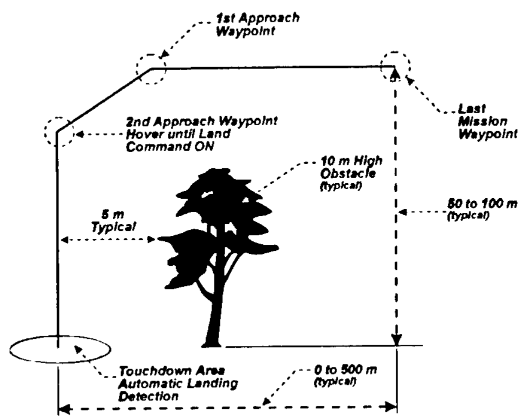


Figure 6-3: Typical Approach Profile

6.2.3 Manual Launch and Recovery

During manual launch, the AV operator commands "Launch" and the AV automatically climbs at a constant rate until it reaches the preset altitude of the first mission waypoint. The AV operator only has to steer the AV in the horizontal plane to reach the first waypoint. During manual recovery, the operator brings the AV above the touch down point using joystick commands. When the AV is hovering above the touch down point, the operator sends "Land Command ON" and the AV descends at a constant rate until touch down. During this descent, the operator simply has to maintain the AV above the touch down point with the joystick.

7. FLIGHT TESTING

7.1 Flight Control Verification

The basic CL-327 pitch, roll, yaw and height controllers will be verified through tether testing and free-flight. As with any free-flight test program, the flight envelope will be expanded around increasing altitude, forward speed, and mass. The basic manoeuvering envelope will also be proven through controlled climbs, dives, turns, accelerations and de-accelerations (tiltbacks). Following this clearance, the improved automatic navigation components of the CL-327 will be tested and flown. Automatic landing and take-off using DGPS will finally be integrated and tested.

7.2 Tether Testing

Prior to the free-flights, many of the basic control design testing will be performed at the Bombardier Flight Center, located in Lawton, Oklahoma.

The ability to tether is unique to VTOL systems and significantly reduces the risk to hardware in a prototyping environment. All the basic autopilots can be tested and proven. Direct collective control allows testing of the pitch, roll and yaw controllers without being at a flight collective, referred to as 'sitting on a pawl', as the AV is not quite supporting its weight. The height-mode system can be tested in full, including height-mode take-offs, hover, and landings. Frequency response and pulse testing are performed at the tether by injecting the signal on the uplink on top of the pilot commands. A high vibration environment is tested by pushing the AV up to 10deg tilt against the wire. The entire navigation control logic and controllers is also tested at the tether by including special test modes in the FCP whereby the height-mode is disabled, the wind estimates frozen, and the AV navigates the waypoints on its own. In case of difficulty the system can be aborted at any time and the engine shut down with no danger to hardware or personnel. In case of failure, the CL-327 on-board Health Manager, which records all warnings and errors that occurred on board the AV from power-up to shut-down, is used as the first line of action in confirming the cause.

8. ONGOING DEVELOPMENTS

8.1 Automatic Flight Patterns

Like other helicopters, the CL-327 vehicle can hover and go straight up and down however, it is more efficient in forward flight. In addition to waypoints, in order to optimize the time on station and range/speed of the AV, the Guidance Function will also include a series of pre-programmed flight patterns. This will allow for advanced manoeuvers such as optimized helicoidal climbs and descents, loitering and hovering, as well as sensor patterns. These patterns can be selected in the definition of a mission plan from the UCS graphical interface.

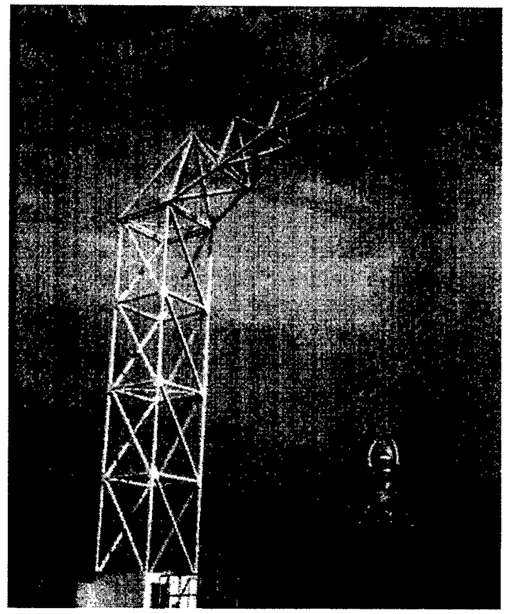


Figure 7-1 : Lawton Oklahoma Tether Test Rig

8.2 Multiple Air Vehicle Operation

The CL-327 allows for simultaneous operation of two AVs, one on station and transmitting data, and one inbound or outbound but not transmitting data as depicted in Figure 8-1. While AV #1 is on-station and transmitting data to the UCS through the main data link (C-band), AV #2 is launched and transits autonomously (silent mode) to a rendez-vous waypoint. This rendez-vous waypoint is in the vicinity of AV #1 but with a safe vertical and horizontal separation. When at destination, AV #2 communicates with AV #1 by providing its position at regular intervals. AV #1 responds by providing target position and AV #2 uses this information to orient the sensor towards the target. AV #1 then requests authorization to return from the UAV Controller; the Controller authorizes the return and then establishes the link with AV #2. Upon receipt of authorization, AV #1 proceeds autonomously towards the recovery point following a collision avoiding path with AV #2.

This feature allows for continuous surveillance of a target with ample time for recycling the AVs.

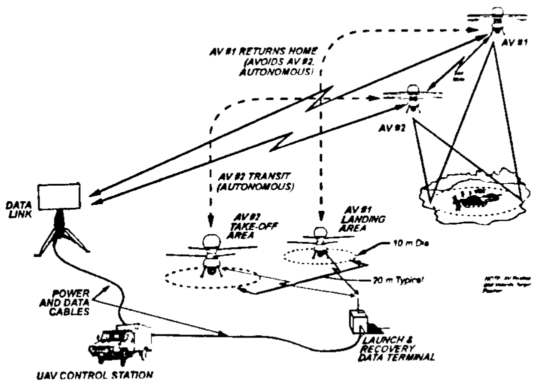


Figure 8-1: Multiple AV Operation Concept

9. CONCLUSION

The CL-327 AV is a robust and reconfigurable system, based on the flight-proven CL-227. The Guidance, Navigation and Control functions provide a high level of automation that reduces operator workload. Because of its specifications and advanced capabilities, the CL-327 AV is the world's most advanced VTOL surveillance system for intelligence gathering, in production today.

10. ACKNOWLEDGEMENTS

The authors would like to acknowledge the help and support of André Chalifoux, Gilles Laflamme, Eric Bouchard and Marc Lambert.

11. REFERENCES

[1] "Canadair CL-227 Sentinel", Flight International, 19-25 April 1995.

[2] Bombardier Inc., Defence Systems Division, "Unmanned Airborne Surveillance and Target Acquisition System (UASTAS)", GAP-DSD-107, November 1996.

[3] Bombardier Inc., Defence Systems Division, "CL-327 UAV System, GCS UAV Software Interface Control Document", DAC 327-102, July 1997.

Reliable Autonomous Precise Integrated Navigation RAPIN for Present and Future Air-Vehicles

Dr. Thomas Köhler - Daimler-Benz Aerospace AG Military Aircraft (Ottobrunn)
P.O. Box 801160, 81663 Muenchen, Germany
Tel: +89-607-24635 Fax: +89-607-32074
E-mail: Thomas.Koehler@otn.lm.dasa.de
Franz Tumbrägel - Daimler-Benz Aerospace AG Military Aircraft (Bremen)
Dr. Jürgen Beyer - Honeywell Regelsysteme GmbH (Maintal)

1 SUMMARY

The operation of unmanned vehicles ranging from strategic missions of autonomous high altitude reconnaissance to tactical missions of reconnaissance and strike/attack impose new requirements to the guidance systems in the area of reliability and safety. This includes all phases of the mission start, cruise, attack/strike and 'Low Level' operation including precision approaches even under bad weather conditions and in a hostile environment.

A reliable, continuous and precise navigation system is of paramount importance for the guidance function even more for unmanned air vehicles. The Project RAPIN, the name standing for 'Reliable Autonomous Precise Integrated Navigation', combines the navigational research activities at Daimler-Benz Aerospace AG (Dasa) Military Aircraft teamed with Honeywell Regelsysteme GmbH in that context. RAPIN integrates 'Laser Inertial Navigation System' (LINS), P(Y) code 'Global Positioning System' (GPS) and 'Terrain Referenced Navigation' system (TRN). The data fusion concept is to combine all available information in one MAIN filter gaining the highest accuracy. In order to provide uncontaminated backup solutions in case of sensor failures a bank of SUB filters is working in parallel. Each SUB filter uses a different subset of sensor signals. It is the objective of this paper to report on the system concept, the design of the prototype, and to describe the realisation process. Subsequently the paper will present first and preliminary results including flight trials on C-160 Transall ANA/FRA (Autonome Navigationsanlage / Flugregelungsanlage) performed by the „Wehrtechnische Dienststelle 61". The possible application of this generic system varies from uninhabited reconnaissance / fighter aircraft over transport aircraft to rescue helicopters.

2 INTRODUCTION

This paper describes the current research and development activities under the lead of Daimler-Benz Aerospace AG (Dasa) Military Aircraft in the field of fault-tolerant integrated navigation systems. After a brief discussion of our motivation we will define the goal and the statement of work of this project. Subsequently we will introduce the involved partners.

2.1 Motivation

Daimler-Benz Aerospace AG - Military Aircraft (Dasa-M) is concentrating on the following unmanned air vehicle (UAV) missions:

- Unmanned high altitude reconnaissance platforms with flight profiles above the current airways (above FL 500) Their use lies predominantly in the areas of peace keeping and crisis control and involves flight over long distances over friendly territory. The flight scenario consists basically of start cruise and landing. Where start and landing incl. penetration of the 'controlled airspace' will take place in a friendly environment with the possibility of direct human control (video & data link). Human involvement during mission (with long delays) is possible via satellite links. In case of jamming or malfunction a „safe termination" function has to be implemented. „Safe termination" refers under these circumstances to a controlled landing in a predefined uninhabited area using a steerable parafoil. These strategic missions experience a long duration from 10hr up to 48hr.

The navigation system has to provide the ability to guide the vehicle to a 'safe' landing facility. The size of the emergency landing places determines the requirement on the navigation system accuracy. Over friendly territory this guidance function is expected to be safety involved with the requirements in system layout (fail-operational) and dependability. Due to the high operating altitude a terrain correlation system is not applicable. It is assumed that a INS/GPS design with the necessary redundancy is appropriate. In case of general GPS unavailability an image correlation system or a star-tracker could aid the navigation system.

- Unmanned autonomous reconnaissance platforms which are operated at medium to low altitudes in a military target area and cruise above FL 200. On their return phase they will operate over friendly territory with the above mentioned requirements regarding safety.

Here a more accurate navigation system is necessary, for the low level operation and the system has to cope with adverse conditions (manoeuvring of the airframe, jamming and other threats by hostile forces). Due to the expected unavailability of GPS in the operating scenario and the low operating altitude a terrain referenced system with its full autonomous non-jamming capability should be employed.

Paper presented at the AGARD MSP Symposium on "System Design Considerations for Unmanned Tactical Aircraft (UTA)", held in Athens, Greece, 7-9 October 1997, and published in CP-594.

- Unmanned tactical aircraft to fly strike and/or attack missions in a conflict. Even though this class of aircraft operates predominately over hostile territory, it will be dispatched from friendly bases and therefore fly partially over friendly territory. Also, to minimise collateral damage, the system accuracy and reliability should match that of current manned aircraft.

The navigation system has to be designed for 'low level' and cruise operations with mixed traffic in the 'controlled airspace'. Still being undefined it is expected that high requirements regarding safety and accuracy have to be met.

As a consequence and to compensate for the missing human on board, all these aircraft need a system architecture which allows to limit the failure probability of the whole system to the same low values which are placed on manned aircraft by the civilian certification authorities if operated over own territory or in peace keeping missions.

Historically the project RAPIN was defined for a transport aircraft with 'low-level operation' capability as the major target scenario. No forward looking radar was permitted in the design. This caused demanding requirements on the navigation function and the digital terrain data base regarding dependability and accuracy.

Reviewing the flight guidance requirements of unmanned aircraft leads to the conclusion that the RAPIN system design has a high potential of fulfilment for UAV needs.

Operating under military conditions the navigation system has also to be operated autonomous, without support from ground stations (risk of jamming, detecting, and destruction of ground stations). As no single state of the art navigation sensor can meet the accuracy, reliability and robustness requirements, integrating well suited individual navigation sensors is presently the only viable solution to this problem.

Even the common used LINS GPS integration is on its own not reliable enough. In order to achieve the position accuracy with the requested reliability for 'low level operations' at least two physically independent position sensors with a similar accuracy are required to co-operate with an additional autonomous navigation system like LINS. This kind of navigation system is where we will focus on in this paper.

2.2 Objectives of RAPIN

The project's objectives have been defined under different aspects.

2.2.1 Strategic Aspect

RAPIN is part of an extensive investigation in the area of low level flight guidance at Dasa which has been started with respect to different applications this decade. In that context RAPIN combines all the navigational functionality research activities.

Moreover RAPIN is the navigational component realisation as a basis of a system which will provide operation of an air vehicle close to ground. Therefore the project RAPIN has been additionally implemented under a technological prototyping aspect in order to achieve the following goals:

- to realise a reliable, precise navigation system, necessary for manned and unmanned low level operations incl. approach and landing of military aircraft as a demonstrator
- demonstrate function and performance in flight tests
- produce generic specification for navigation systems for future product applications with requirements regarding high dependability
- build up supplier's system relevant realisation know how

As a realisation restriction all the existing navigation components have to be used unchanged, which is due to some system implementation benefits and aviation administration requirements as well.

2.2.2 Operational Aspect

RAPIN is focusing on military low level flight operation scenarios. Present and future mission requirements of military air vehicles, stand-off-weapons, drones, transport aircraft and of unmanned tactical aircraft dictate accurate and dependable navigation as a means to increase survivability and mission effectiveness. Navigation systems will be increasingly used to deliver precise position, velocity and track data to the flight control system to guide aircraft during low level flights (approach and landing, terrain following, terrain and threat avoidance). In this case, the navigation signals are flight safety critical and the dependability (integrity, continuity, survivability and availability) becomes the major system requirement.

Especially in unmanned air vehicles like military reconnaissance UAV's or uninhabited fighters, which have a long flight-endurance not only above war-theatres but even over inhabited areas, the navigation system reliability is even more important than in manned aircraft. Here, no pilot can verify the correct operation of the avionics-system and can take over system-control if a system-failure occurs.

Thus autonomous navigation components are favourable for system survivability, availability and continuity reasons. Redundancy will be stressed in terms of system reliability and integrity. Due to jamming in the hostile environment P(Y) code GPS is seen to be useful as an aiding sensor albeit having to play a 'nice to have but add on' role in the system concept.

A secondary objective of project RAPIN in that context is answering the question whether military precise approach and landing is possible in terms of accuracy using a P(Y) code GPS receiver and/or TRN instead of a differential D-GPS system.

As no single navigation sensor can meet the accuracy, dependability, and robustness requirements, integrating the well suited individual navigation sensors is the only viable solution approach to meet all operational requirements.

2.2.3 Realisation Aspect

The RAPIN objective is, to develop a single lane navigation system prototype as a basis for an on-board autonomous flight guidance system with a low level and approach and landing capability and to perform a functional and accuracy performance assessment.

The main target within the RAPIN navigational integration process is the adequate sensor fusion and the optimal signal filtering. Thus proof of concept and filter software development with respect to verification ability and flight clearance found a considerable interest in the project and in this paper respectively. Concept verification has been conducted via various and extensive lab and test trials.

2.3 Technical Requirements of RAPIN

The technical requirements are deduced from the mission operational requirements.

A typical military mission is principally divided in the phases with varying duration:

-start
-cruising to the operation area in high altitude
-operating in low level height above terrain
-cruising back to home base or another air base
-approach and landing. See figure [1].

This scenario requires a navigation system with sufficient accuracy and dependability to allow low level operation, approach and landing and to meet the required mission reliability. Furthermore, for military missions the avionics has to be 'on-board autonomous'. Figure [2] shows the dependence of the RAPIN system concept from the operational and technical requirements.

For the manned aircraft only the phases of 'Low Level Flight' and 'Approach and Landing' are design drivers for an integrated navigation system. For unmanned aircraft all phases of flight are critical.

Position requirements are usually defined as Total System Error (TSE) being composed of the Navigation System Error (NSE - accounting for errors in the equipment) and the Flight Technical Error (FTE - accounting for guidance errors of the pilot and autopilot). Here only NSE are used to express accuracies.

2.3.1 Low Level Flight

'Low Level Flight' begins at heights less than 1000ft (304m) agl down to 100ft (30m) agl for terrain following and down to less than 10m for load dropping. It is performed to protect the aircraft from detection and threats in hostile areas. There are no common accepted performance requirements. As a goal we use the following preliminary requirements:

Parameter NSE	unit	values
Horizontal Accuracy	[m] 2σ	< 200
Vertical Accuracy	[m] 2σ	< -2 / +4 **
Integrity Risk	[@1hr]	$< 1.0\ 10^{-5}$
Availability Risk	[@1hr]	$< 1.0\ 10^{-2}$
Continuity Risk	[@1hr]	$< 1.0\ 10^{-3}$

** or -3% / +6% of Height above ground level (30-300m) whichever is greater.

An integrity violation can cause a CFIT (controlled flight into terrain) accident. An availability violation causes a mission abort in areas without threat. A continuity violation may lead to a mission abort and termination of the 'Low Level Flight' thus reducing the aircraft protection in a hostile environment.

2.3.2 Approach and Landing down to CAT II

'Approach and Landing' phase of flight is typically performed in areas controlled by friendly forces. Various requirements are in discussion for the civil aviation regarding replacement of ILS technology. See [24] The tunnel approach is used as a reference for a CAT II type landing:

Parameter NSE	unit	values
Horizontal Accuracy	[m] 2σ	< 22,8
Vertical Accuracy	[m] 2σ	< 4,4
Integrity Risk	[@1hr]	$< 3.3\ 10^{-8}$
Availability Risk	[@1hr]	$< 1.5\ 10^{-3}$
Continuity Risk	[@15sec]	$< 4.0\ 10^{-6}$

Assuming a FTE of 2,3m cross flight direction and 1,15m vertical see [26].

Further investigations are required in order to decide whether these civil requirements, based on fleets of 200 aircraft with 50.000 operating hours, are applicable to the military scenario.

2.3.3 Cruise

During the cruise phase the radar altimeter and the terrain correlation will not be available. The requirements are comparable with civil aviation were GPS and LINS are a sole means of navigation. The quick phase over to low level flight accuracy is given by the availability of the R/A at 5000ft height above ground level. Mission duration may vary between 2hr up to 48 hr for reconnaissance missions.

Parameter NSE	unit	values
Horizontal Accuracy	[nm] 2σ	< 12.6
Vertical Accuracy	[m] 2σ	< 50m
Integrity Risk	[@1hr]	$< 1.0\ 10^{-5}$
Availability Risk	[@1hr]	$< 1.0\ 10^{-3}$
Continuity Risk	[@1hr]	$< 1.0\ 10^{-4}$

2.4 Project Organisation and Teaming

The need for a navigation system like RAPIN was recognised by the 'Bundesamt für Wehrtechnik und Beschaffung' (BWB) and a Research & Development contract was granted to Daimler-Benz Aerospace AG Military Aircraft teamed with Honeywell Regelsysteme GmbH to investigate the system concept and perform flight demonstrations with a prototype system.

The Wehrtechnische Dienststelle WTD61 (from German MoD) in Manching is the responsible team partner in the RAPIN programme. The operation of the flight test aircraft, the necessary instrumentation, the continuous position reference using the AN/MPS36 radar tracking system and the recording of all data is performed by WDT61.

System concept, design, build, integration and test of the system is performed by Dasa, the Kalman filter bank design and LINS support is provided by Honeywell.

3 RAPIN SYSTEM CONCEPT

Purpose of this chapter is to present the RAPIN system overview followed by a description of the system and its components. It ends with the discussion of the general verification concept.

3.1 System Overview

The system overview describes the basic ideas in order to develop an integrated navigation system which fulfils all objectives of military operations especially where safety relevant-navigation plays an important role (e.g. low level flight). The

chapter also discusses these ideas and describes the approach followed by RAPIN.

3.1.1 *Basic Ideas*

The RAPIN system concept is based on the integration and optimal exploitation of navigation components, which are typically on board of military aircraft. These are a Laser Inertial Navigation System (LINS), a Global Positioning System receiver (GPS) (operating in the high military accuracy Precise Positioning Service, PPS mode or P(Y) code), an Air Data Computer (ADC) and Radar Altimeter (R/A). Additionally RAPIN uses a Terrain Referenced Navigation system (TRN) based on the Dasa system LATAN (Low Altitude Terrain Navigation), which utilises the R/A and compares its measured altitude over terrain profile with a profile of an on board terrain data base in order to find the best fit.

With this concept the integrated navigation system has sufficient signal redundancy available as parallel- and principal redundancy. In order to make adequate usage of that redundancy RAPIN is comparing solutions of a bank of four Kalman filters to increase the dependability. One MAIN filter utilises all available information; three SUB filters make use of different dedicated sub sets of sensor components.

3.1.2 *Discussion*

It is well known that LINS as an on board system has high reliability and medium long term accuracy. GPS is a very accurate sensor but leaks in terms of dependability especially with respect to continuity. The autonomous system LATAN perfectly fills the gap while having a good accuracy and a high continuity.

The table in figure [4] shows pro's and con's of each sensor in more detail.

In order to obtain high 'all the time accuracy' combined with high dependability RAPIN integrates all sensor signals in one MAIN filter. The integrity is achieved via self checking in parallel to cross monitoring of the MAIN filter solution versus the solutions of the three SUB filters mentioned above. Thus in case of a failure detection at least one uncontaminated solution is available. While providing a monitor function in conjunction with elaborated failure detection and isolation (FDI) methods RAPIN guarantees the necessary terrain following navigation robustness.

3.1.3 *Approach*

This paragraph describes in detail the approach taken to realise the RAPIN navigation.

Due to the generic integration of navigation sensors RAPIN relies generally on the existing sensors already fitted in the Transall C160 ANA/FRA test aircraft at the WDT61. The fixed definition of the LINS interface limits this experimental implementation of RAPIN to the Open Loop Kalman filter solution which easily is expandable to the Closed Loop configuration if interfaces are changed.

The characteristics of the LINS, GPS and ADC sensors are given in detail in chapter 'System Components'. The existing radar altimeter was not used due to interface limitations in the C160 Transall aircraft. Therefore a Dasa supplied DRA100 was integrated.

The signal processing and interfacing with all sensors is exercised by a flight ruggedised VME based 'Commercial Of The Shelf' (COTS) computer from Harris Type: 6804 which was integrated in the C160 by WTD61.

Navigation software is based on the proven 'Navigation Laboratory' (NavLab) from Honeywell. This includes a generic configurable Kalman filter, the necessary simulation and the trajectory generation facilities. The PASCAL based NavLab was converted to HO language 'C' and modified to reflect the RAPIN needs. The tested kernel routines are used in the Real Time (RT) environment without any changes. This relates to the verification concept including the 'Software In the Loop' simulation and 'Hardware In the Loop' simulation described later.

For the terrain correlation software package the proven 'Low Altitude Terrain Aided Navigation' (LATAN) and the related 'Terrain Data Base' (TDB) from Dasa is used. The PASCAL based LATAN was converted without major changes to the HO-language 'C'. LATAN and the TDB were adapted to the RAPIN needs.

All software was integrated into the Harris Real Time processing environment.

The final tests constitute the operational flight tests which began in 1997. These tests will be continued in 1998.

3.2 System Description

The system description will address the overall RAPIN system overview and the architecture of RAPIN data fusion.

3.2.1 *Overall System*

A generic system concept is depicted in figure [5].

The outlined boxes show the kernel sensor set comprising the true autonomous components 'Laser Inertial Navigation System' LINS, 'Air Data Computer' ADC, Radar Altimeter R/A and the board-autonomous components 'Global Positioning System' GPS (operating in the high military accuracy Precise Positioning Service, PPS mode, P(Y) code) and the On-Board Terrain Data Base (TDB), each in sufficient parallel hardware redundancy. To these sensors the software implemented Terrain Referenced Navigation (TRN) function is added as a further positioning system by combination of the Radar Altimeter data and the On-Board Terrain Data Base data via a terrain correlation.

The dashed boxes show possible extensions of the sensor set which are 'nice to have' if useable but not 'to rely on'. LORAN-C may be of interest for marine applications due to the lack of availability of the terrain correlation function over water. The image referenced navigation is a further extension which has the potential to provide an autonomous position sensor for altitudes where no radar altimeter is available and to improve the landing phase of the mission significantly, by not only updating the navigation solution, but also delivering a readable real outside view e.g. by infrared or millimetre radar (see Lerche, Tumbrägel Ref. [27]). ILS and MLS are for compatibility with civil aviation requirements.

The signal processing hardware contains a copy of the terrain database each, the information is cross fed and frame synchronised by 'Computer-Computer-Direct-Links' (CCDL) and the

power supply is realised separately and without feedback possibility by connection to at least two power bars.

The optimal exploitation of signal redundancy (data fusion) is done by a modular reconfigurable „Extended Kalman Filter" , used as an observer of the parallel existing real world. Figure [3] shows the sensor integration, figure [4] characterises the features of each subsystem and the integrated RAPIN solution according to the major requirements.

The RAPIN system concept is given in figure [6] including the functions Kalman filter bank, terrain correlation, sensor failure detection and isolation (FDI), system FDI - single lane, system FDI - cross lane and the redundancy management.

3.2.2 Architecture of Datafusion

As already described in '3.1 System Overview' the navigation system RAPIN integrates LINS, P(Y) code GPS and TRN.

Because of the system immanent instability of the LINS vertical channel in an 'open loop' architecture, pressure altitude aiding has to be provided via the air data computer ADC. Also TRN needs a radar altimeter R/A as an additional sensor in order to measure the altitude profile with respect to terrain. Thus in this chapter we will talk about LINS only in a LINS/ADC combination and we will see TRN always in conjunction with a R/A.

Obviously the primary RAPIN data fusion concept is to combine all LINS, GPS and TRN information in one MAIN filter in order to gain the highest navigation accuracy possible.

To provide uncontaminated backup solutions even for the worst case failures (slow ramps), which are detected only a long time after their occurrence, a bank of SUB filters is working in parallel to the MAIN filter simultaneously . Each SUB filter uses a different subset of sensor signals. Thus RAPIN consists additionally of a LINS/GPS filter, a LINS/TRN filter and a TRN/GPS filter respectively.

Figure [7] shows the RAPIN filter scheme.

Each RAPIN filter, no matter whether MAIN or SUB, is using the same extended Kalman filter module. Via an index vector the various filter models are easily configurable with respect to the sensors involved. An additional benefit of this index vector is the smooth adaptation to different sample rates and the easy to use reconfiguration mechanism in the case of detected and isolated failures. Failure detection and isolation (FDI) function is accomplished by the RAPIN redundancy management module. The filter bank contributes to the FDI function via providing estimated sensor errors in all the different filter combinations.

Effort and importance of an appropriate signal synchronisation appears to be underestimated very often. In order to calculate proper residuals for all different filters high attention was paid to that topic of the datafusion.

3.3 System Components

In the following each major system component is described.

3.3.1 Sensors

These sensors are integrated in the test-aircraft C160 ANA/FRA and are used unmodified for the RAPIN navigation system.

LINS: Honeywell H-423 LINS (SNU 84)
Position Accuracy <0.8 nmph (CEP)
Velocity Accuracy < 2.5 ft/s (RMS)

GPS: Rockwell Collins MAGR 3M PPS
Position Accuracy < 16 m (SEP)
Velocity Accuracy < 0.1 m/s (RMS)

ADC: GEC-Marconi (HIADC)
Pressure Altitude Accuracy < 15 ft or 0.2% Hp

The Radar-Altimeter (R/A) is a prototype of Dasa-LFK with high accuracy. It was integrated in the test-aircraft as part of the RAPIN project.

R/A: Dasa DRA 100
Position Accuracy 2 ft or 2% of the height_agl
Maximum Height: 2400 ft (750 m)

3.3.2 Signal Processing

The Real Time signal processing is performed on a flight ruggedised Harris Nighthawk 6804 with 4 processors and local recording of 4 Gbyte. For the verification a second Harris is used in the HIL and SIL test rig simulating the Transall environment.

3.3.3 Terrain Data Base

The terrain database (TDB) consists of different raw databases i.e. the Digital Terrain Elevation Data (DTED), the Digital Feature Analysis Data (DFAD) showing the natural and artificial surface (forest, city etc.) and the Obstacle Data ('Luftfahrt Hindernis Datei', LFH) showing artificial structures that can cause a hazard for low level operation (towers, power lines etc.). This data is processed in the off line component of the TDB to generate the input for the on-board component. The off line functions include merging and cross checking of databases with e.g. satellite data, data compression, data conversion, assembling of mission related data to provide a data set that can be uploaded to the on-board TDB. The function of the on-board TDB basically is to distribute the data in a timely manner to the data sinks, here the terrain correlation. In the low level guidance system other data sinks are the display and the ground proximity warning system etc.

3.3.4 Terrain Correlation or Terrain Referenced Navigation (TRN)

The Terrain Referenced Navigation is based on the LATAN system. LATAN is a navigation and Terrain Following (TF) system based on terrain reference data stored in an on board data base. It has been developed by Daimler Benz Aerospace AG Military Aircraft Division (former MBB) and flight tested on the TORNADO aircraft between 1986 and 1993. The algorithm of the LATAN navigation function has been separated from the whole system and is implemented in the RAPIN computer. The LATAN principle is shown in figure. [11].

Terrain Profile Generation

Along the ground track, the profile of the terrain to be flown over is measured via the radar altimeter in parallel to the 3 dimensional aircraft trajectory measured by the navigation system (e.g. INS or GPS) used as a navigation position hypothesis. Thus the terrain elevation is determined by the difference between the height above sea level (e.g. Baro-IN height or GPS-height) and the height above ground level (radar height).

This measured terrain profile is correlated continuously with reference profiles from the on board terrain data base which are stored with their exactly known positions.

Horizontal Position Determination

Along the measured ground track, reference terrain profiles are generated with the stored terrain data base by varying the position hypothesis of the ground track. The position variation with the profile which has the best fit to the measured terrain profile is the correction of the horizontal position hypothesis. The quality of the horizontal position depends on the terrain significance.

Vertical Position Determination

The vertical position is determined by the mean difference of the measured terrain profile and the reference profile at the best available horizontal position. The quality of the vertical TRN position is independent from the terrain significance. This is very important for approach and landing where precise height above ground level is the most critical parameter. Therefore the vertical channel is fully independent from the horizontal channel and provides a higher update rate.

3.3.5 Data Synchronisation

For aircraft speeds of e.g. 400 kts a synchronisation error of 20msec is equivalent to 4m position inaccuracy.

The data fusion is essentially based on measurements of different position sensors. Each measurement has its own time of validity. Some sensors have high measurement update rates like the LINS (20msec) others like GPS rather low (1sec), the terrain correlation does not have a fixed update rate but is rather dependent on aircraft speed and terrain due to its correlation length dependency.

Each sensor knows its time of validity and time tags its message. At the point in time where the difference is generated for the data fusion the system knows the age of the data.

Differences with respect to the high rate sensors e.g. LINS can be built by storing the raw LINS data or the optimally estimated data in a buffer and selecting the appropriate value. If further refinement is necessary interpolation is possible. Differences with respect to low rate sensors are based on buffering velocity extrapolated data with the associated reduction in accuracy.

3.3.6 Kalman Filter Module

In order to handle the system design efficiently a flexible Kalman filter algorithm has been developed which allows to define all RAPIN SUB filters directly from the RAPIN MAIN filter by the simple change of parameters, indexes and moding.

The general RAPIN navigation filter state vector consists of 9 elements
attitude and heading estimates
navigation velocity estimates
position and altitude estimates

In the classical 'open loop' mode navigation estimates are identical to LINS errors. In the 'closed loop' mode the estimates are directly the most precise navigation signals.

The 6 Inertial Measurement Unit (IMU) errors are
x,y,z, gyro random constants estimates
x,y,z, accelerometer random constants estimates

P(Y) code GPS errors are 6 elements
navigation velocity random constants estimates
position and altitude random constants estimates

The 3 TRN errors are
position and altitude random constants estimates

One Barometer error is
altitude random constant estimate

One Radar altimeter error is
altitude over terrain random constant estimate

Obviously the RAPIN MAIN filter is using all 26 states mentioned above. The LINS/GPS SUB filter consists of the navigation (including barometer) vector, the IMU and the GPS component, which sums up to 22 states. With respect to the LINS/TRN filter we count 19 states, namely navigation (including barometer), IMU and TRN errors. Finally the TRN/GPS filter has 6 navigation, 3 TRN, 6 GPS plus 4 additional track states (track-velocity, -acceleration, -angle, -rate).

Each RAPIN filter index vector addresses its state elements and the involved sensor signals. The initialisation of states and state error covariances as well as system and sensor covariances are primarily identical under a physical perspective. From a filter point of view they are to be used as filter fine tuning parameters in order to optimise the filter performance. The time variant error covariance calculation needs the integrated navigation system's transition and its sensor matrix. Both matrices are determined via linearisation along the trajectory. In 'closed loop' architecture the linearisation trajectory is identical to the best filter estimate and thus we obtain an almost classical extended Kalman filter structure. In 'open loop' architecture raw LINS and as well as filter corrected LINS trajectories are available for linearisation.

The Kalman filter module architecture is able to use all mentioned linearisation variants in order to obtain both integrated system's matrices (system and sensor).

3.3.7 Navigation Algorithm

Navigation and Kalman filter algorithms used in RAPIN have been developed in the software toolbox NavLab. Thus NavLab is an important part in the RAPIN software development environment. The NavLab package is property of Honeywell Regelsysteme GmbH, Maintal.

NavLab is written in PASCAL language and implemented on PC/MS-DOS and Macintosh computers. The NavLab program development started in 1990. For more background information see Köhler [5], Beyer [6] and figure [9].

Main components of NavLab are
Navigation generator
Sensor data generator
Strap-down algorithm
Extended Kalman filter
Conventional filters
Navigation analysis

All trajectory and parameter manipulations like
time, duration, sample rates
Navigation modus
Trajectory inputs
Trajectory disturbances
Generator steering data

Sensor error data
Strap-down data
Kalman filter parameter
Kalman filter configuration
Output modus
are accomplished via an ASCII parser file.

Available analysis methods in NavLab are
Monte Carlo simulation
Error covariance analysis
sample run in combination with filter covariance
which are used widely in RAPIN.

3.3.8 *Failure Detection and Isolation*

The failure detection and isolation task is to derive information about the condition of the system and sensors. It does not make any decision. It is hierarchically organised from simplex to complex. Its outcome is a set of status words belonging to two classes OPERATIONAL STATE and HEALTH.

The following order of tests with increased complexity is used:

- sensor Built In Test assessment
- sensor operational sensor state
- sensor plausibility test stand alone
- sensor gradient test

For each filter in the bank:

- sensor plausibility test with regard to optimal selected output
- sensor parameter estimates test (Kalman filter)
- sensor operational filter state

For each lane:

- System Kalman filter cross lane test
- sensor operational lane state

For all lanes:

- System cross lane tests
- sensor operational system state

Each Health test can declare a component HEALTHY, SUSPECTABLE or DEFECT. A healthy sensor shows no errors or failures at all, a suspectable sensor has shown some errors which are small or of short duration (spike) and a defect sensor exhibits major errors for longer periods of time.

Each Operational State test gives information whether the component has received data, has send data, is synchronised, is in initialisation or is suspended etc.

3.3.9 *Redundancy Management and Moding*

The redundancy management is to assess the outcome of all tests and to derive a decision whether to use or not to use a sensor/component in the system solution.

The system has three decision levels:

- after sensor input - to decide which sensor to synchronise
- after synchronisation - to decide which sensor inputs are useable for the filters
- after filter bank -to decide which filter is to be placed to the output

Decision making is twofold. First the relevant status words have to be condensed to a decision level status word, e.g. sensor channel has received data AND BIT test AND plausibility test AND gradient tests signal healthy data THEN sensor data may be synchronised. Secondly the decision status word has to be interpreted in a decision process.

This decision process in level three is for example to copy one of the filter solutions into the output buffer depending on the relevant decision status word.

3.4 Data Fusion Layout

With respect to hybrid systems it has to be stated that the minimisation of uncertainty in the system via more complexity is limited. This is due to fact that performance improvement means more sensor dependence in the same way. Nevertheless a more complex hybrid system presently seems to be the only way towards a safe low level flight navigation system. It is obvious that the approach of sensor signal information processing becomes most important in that context. As the way of analytical interpretation defines the approach two possible but different point of views in navigation will be presented and discussed next.

3.4.1 *Signal technical Interpretation*

In its signal technical interpretation the navigation process is a sequential approach which focuses on the Inertial Measurement Unit (IMU). Measured IMU accelerations and turnrates in the body coordinate system are processed in the Strapdown Algorithm (SDA). The SDA calculates the inertial navigation signals. IMU and SDA are the main components of a Laser Inertial Navigation System (LINS). In order to improve the inertial solution, aiding sensor signals are compared to them. Via Kalman filtered residuals the inertial navigation errors can be estimated. The optimal filter result is the corrected inertial solution. Major problem of this approach is the mix of measured sensor signals and theoretical navigation model. Therefor noise on the IMU signals is disturbing the analytical platform of the SDA. The correction of the inertial navigation solution via the estimated inertial errors is only sub-optimal due to the integrated IMU sensor noise. Additionally stochastical IMU sensor error parameters have to be erroneously modelled as system noise in the Q-matrix of the Kalman filter (see also Beyer [6]). Nevertheless the optimal blending filter derived with respect to this signal technical interpretation is the common used approach in navigation. It is showing good results since IMU errors and noise are small. The inertial trajectory of the LINS is typically used to determine the linearised Kalman filter model matrices.

3.4.2 *Mathematical Monitor Interpretation*

In the new developed mathematical monitor approach all sensors and systems like LINS, GPS and TRN are equally ranked aiding sources since the monitor uses a sensor signal independent navigation model internally. Fictive sensor signals are derived from the navigation model and specific sensor models. Providing this calculated fictive sensor signals which are compared to the real sensor signals, the only way the sensor signals contribute to the navigation solution is via the residuals of the

extended Kalman filter used. Since all fictive sensor signals are derived from the monitor's independent navigation model and are adapted to the specific sensor signals via additional sensor models, the monitor automatically combines all available sensor information in one optimal single estimation state. The output contains this mean values plus the related one sigma error estimations from the Kalman filter covariance matrix. Due to its sensor independent navigation algorithm the monitor system model is easy to extend and easy to adapt respectively. The stringent sensor and navigation model separation enables a straight forward Failure Detection and Isolation (FDI) implementation.

3.4.3 Application to RAPIN

Since time continuous LINS data are available the RAPIN MAIN filter, the LINS/GPS SUB filter and the LINS/TRN SUB filter have been designed using the signal technical interpretation. The discontinuous nature of TRN and GPS signals motivated the mathematical monitor approach development. which has been adapted to the TRN/GPS SUB filter in RAPIN.

3.5 Verification Concept

The verification of the RAPIN system is separated in:

- Module Tests, for testing each sub-function (controller. Kalman Filter, terrain referenced navigation. terrain data base, signal-interfaces) in dedicated test environments.
- Software In the Loop (SIL) tests for test and optimisation of the complete RAPIN software (Controller. TRN. Terrain Data Base. Kalman Filter , Failure Detection and Isolation. Moding) in the functional development environment.
- Hardware In the Loop (HIL) tests which are necessary for testing the RAPIN computer under realistic aircraft interface conditions in real time. before it is installed in the aircraft.
- Flight Trails for proofing the system performance under operational conditions of military aircraft missions.

For reducing the number of test flights. a forcing tape is generated form the recorded data of each flight for rerunning the flight in the SIL- and HIL-environment with simulated sensor failures and errors via failure generator.

4 RAPIN RESULTS

RAPIN results are presented in form of simulations and preliminary flight test data.

4.1 Simulations

Following. an example of simulation results are reported for NavLab-simulation with synthetic generated sensor data.

All the filter initialisation and parameters have been tested and tuned in NavLab simulations prior to follow on test procedures. Thus all state vectors, the state vector error covariances. the sensor covariances and the system covariances have been fixed preliminary. The calculated time history of each filter became the reference in all later on tests. After each flight test the initialisation and parameters had been compared and updated with respect to the gathered real data. Due to this iterative process our confidence is high that NavLab simulations meet the reality very well. With respect to that the complete RAPIN filter bank tuning using different simulated trajectories as well as simulated sensor error stimulations is very effective in time and cost respectively.

As an example figure [10] is showing a simple one sigma time history simulation from RAPIN MAIN filter created for test purposes. The run is starting with LINS in stand alone mode: at time 10 sec the barometer aiding is activated: at time 4 min TRN is added: at time 5 min a right hand 90° heading change is initiated: at time 6 min GPS is added. The simulation ends after 700 sec.

4.2 Flight Tests

The RAPIN flight tests are divided in 5 campaigns:

1. Integration flights for approving the operation of the RAPIN system in the C160 Transall. set-up the data gathering. and the reference system AN/MPS36.
2. Performance tests of the RAPIN sensors during different flight conditions (height variation influencing the ADC and Radar Altimeter. varying the overflown terrain significance influencing the TRN performance. aircraft manoeuvres influencing the LINS- and GPS-performance) and the performance of the RAPIN system under this conditions.
3. Performance tests of the TRN over extreme flat terrain and the influence on the RAPIN system and Radar Altimeter tests during flights over sea. Therefore flight trails will be done in northern Germany.
4. High precision performance tests during approach and landing.
5. Long range flight tests.

4.2.1 Test aircraft C160 Transall ANA/FRA

The RAPIN test aircraft is a German Airforce Transall C160 with the ANA/FRA system upgrade installed operated by the WTD61 of the German MoD. See figure [8].

4.2.2 Reference Data

The reference trajectory of the RAPIN test aircraft is measured by the AN/MPS36 tracking radar. operated by the WTD61 of the German MoD. With a maximum range of 150 km its accuracy is:

Azimuth Accuracy:	0.01deg	(RMS)
Elevation Accuracy:	0.012deg	(RMS)
Range Accuracy:	2m	(RMS)

Which translates roughly to:

North - East Accuracy:	4 m @ 25 km distance	(RMS)
Altitude Accuracy:	5 m @ 25 km distance	(RMS)

Unavailability of the AN/MPS36 reference data by operations close to the ground. maximum range of approx. 150 km and the limited accuracy for altitude led to the decision to install a DGPS reference system in the test-aircraft for the future low level and long duration flight tests. The errors shown in the flight test results are differences of RAPIN outputs and the AN/MPS36 reference system.

4.2.3 Data Analysis

As an example the results of the flight at the 25th March 1997 will be discussed. The flight profile is classified as low cruise flight. The flight consists of start and climb to altitude 1150m, two loiter turns and climb/dive manoeuvres between 1000 m and approximately 1900 m return to base and landing. The height agl is beyond the maximum range of the R/A so no TRN is available. Figure 12 and 13 shows the horizontal and vertical flight trajectory.

Performance of the MAIN filter LINS/GPS/TRN

The horizontal position error of the MAIN filter is 14 m R95 (as can be seen in figure 14) which relates to a 7 m CEP. In figure 16 and 17, the difference between the AN/MPS36 tracking radar and the RAPIN system output is plotted for the North- and East-position in conjunction with the Kalman Filter calculated standard 1 σ deviations (square root of the covariances). This graph shows the conservative filter design containing the error in the covariance band. The altitude channel shows in figure 15 the 2 σ error bound to be 10 m resulting in a 5 m RMS error. This preliminary result can still be optimised by tuning the filter parameters. The gaps in the error plots (figures 15, 16, 17) are caused by AN/MPS36 tracking radar outages.

4.3 Filter Optimisation

The filter optimisation will be done at a later stage of the project by using the 'forcing tape' technique. Here the recorded flight test data will be 'replayed' in either the HIL test rig under full real time conditions or in the SIL test environment with access to all internal variables but in an off-line fashion.

5 OUTLOOK

The project is now in the phase of flight testing and optimising the single lane prototype functionality. The flight test phase will last until 1998. The optional project extension in 1998 includes the extended investigation of fault behaviour and the final assessment of performance.

The investigated system concept of RAPIN is a general purpose navigation system with a modular extendible and adaptable design that can be used in the whole scenario of flight safety critical applications where navigation data is involved.

The next steps in the refinement of this navigation concept is the assessment of the dependability figures of the overall system and integration of further navigation sensors like LORAN-C or image referenced navigation sensors (see Lerche, Tumbrägel Ref. [27]).

6 REFERENCES

[1] Britting, K. R.; Inertial Navigation Systems Analysis. Wiley-Interscience 1971, ISBN 0-471-10485-X

[2] Gelb, A.; Applied Optimal Estimation. The M.I.T. Press. 1986, ISBN 0-262-70008-5

[3] Bryson, Arthur E. Jr.; Ho Yu-Chi: Applied Optimal Control; Hemisphere Publishing Corporation 1975 ISBN 0-89116-228-3

[4] Taschenbuch der Navigation Teldix GmbH 1979

[5] Köhler, Thomas; Sicherheits- und Genauigkeitsprobleme multifunktionaler Trägkeitsensorsystem für Flugregelung und Navigation, Darmstädter Dissertation 1992

[6] Beyer, Jürgen; Nichtlineare Schätzung inertialer Navigationsgrößen durch die fehlertolerante Verarbeitung zusätzlicher Stützinformationen, Darmstädter Dissertation 1993

[7] Sage A. P. , Melsa J. L.: Estimation Theory McGraw-Hill, Inc 1971

[8] Brammer K. , Siffling G.: Stochastische Grundlagen des Kalman-Bucy-Filters Zweite Auflage, R. Oldenbourg Verlag, München/Wien 1986

[9] Brammer K. , Siffling G.: Kalman-Bucy-Filter Zweite Auflage, R. Oldenbourg Verlag, München/Wien 1985

[10] Schrick K. W.: Anwendungen der Kalman-Filter-Technik Erste Auflage, R. Oldenbourg Verlag, München/Wien 1977

[11] Krebs V.: Nichtlineare Filterung Erste Auflage, R. Oldenbourg Verlag, München/Wien 1980

[12] AGARD-AG-254 Advances in Inertial Navigation Systems and Components AGARDograph No. 254, 1981

[13] Navtech Seminars, Inc.: ION GPS-92 Tutorials Albuquerque, New Mexico, September 14-15, 1992

[14] AGARD-LS-133 Advances in Strapdown Inertial Systems AGARD Lecture Series No. 133, 1984

[15] Scherzinger B. M.: General Description of In-Air Alignment and Navigation Honeywell ATC, Markham, Ontario 1989

[16] Scherzinger B. M.: Integrated Navigation System Design Applied Analytics Corporation, Willowdale, Ontario 1991

[17] AGARD-LS-166 Kalman Filter Integration of Modern Guidance and Navigation Systems AGARD Lecture Series No. 166, 1989

[18] Willsky A. S.: A Survey of Design Methods for Failure Detection in Dynamic Systems Automatica, Vol. 12, pp 601-611 Pergamon Press 1976

[19] Brumback B. D. , Srinath M. D.: A Chi-Square Test for Fault-Detection in Kalman Filters IEEE Transactions on Automatic Control, Vol. AC-32, No. 6, June 1987

[20] Willsky A. S. , Jones H. L.: A Generalized Likelihood Ratio Approach to State Estimation in Linear Systems Subject to Abrupt Changes The Analytic Sciences Corporation, Reading, Mass., under USAF Contract No. F04701-74-C-0095

[21] Carlson N. A. , Kerr T. H. , Sacks J. E.: Preliminary IR-MA 321 Integrated Navigation Concept Study Intermetrics Inc., Cambridge, Massachusetts, June 1984

[22] Kerr T. H.: A Critique of Several Failure Detection Approaches for Navigation Systems IEEE Transactions on Automatic Control, Vol. 34, No. 7, December 1989

[23] ICAO Aeronautical Telecommunications - Annex 10 - Fourth Edition of Volume 1, April 1985

[24] Minimum Aviation System Performance Standards DGNSS Instrument Approach System: Special category I (SCAT-I); RTCA/DO-217 August 27, 1993 by SC-159

[25] Integrated Vehicle Management Systems ; AGARD-Advisory Report 343; April 1996

[26] Continuity Improvements via Inertial Augmentation of GPS based landing system; Ping-Ya Ko, Per Enge, J. David Powell, Stanford University, IEEE Position and Location Symposium 1996

[27] Radar seeker based autonomous navigation update system using topography feature matching techniques; H. D. Lerche, F. Tumbrägel AGARD-CP-524 Advances in Guidance and Control of Precision Guided Weapons Nov. 1992

7 APPENDIX

7.1 Abbreviations

ADC	Air Data Computer
AGARD	Advisory Group for Aerospace Research & Development
agl	above ground level
ANA	Autonome Navigationsanlage
CAT	Operational Performance Category (ICAO-Annex 10)
FRA	Flugregelungsanlage
GPS	Global Positioning System
HIADC	High Integrated Air Data Computer
LATAN	Low Altitude Terrain Aided Navigation
LFK	Lenk Flug Körper
LINS	Laser Inertial Navigation System
NavLab	Navigation Laboratory
P(Y)	Precision-Code (encrYpted) GPS
RAPIN	Reliable Autonomous Precise Integrated Navigation
R/A	Radar-Altimeter
RTCA	"Requirements and Technical Concepts for Aviation" (new) Radio Technical Commission for Aeronautics (old)
SDA	Strap Down Algorithm
TDB	Terrain Data Base
TRN	Terrain Referenced Navigation
UAV	unmanned air vehicle
UTA	unmanned tactical aircraft

7.2 Definitions / Terms

The following definitions / terms are used throughout the paper:

'Low Level': low height above ground level with height < 1500 ft

'Low Level Flight Operation': e.g. terrain following, terrain/threat avoidance, load dropping, reconnaissance; target designation; weapon aiming and delivery etc.

'Terrain Following Operation': guiding the aircraft over the terrain with a set clearance height in the range of 1500ft down to 100ft with less than 1000ft recommended.

'Military Aircraft': transport aircraft, manned and unmanned tactical aircraft, helicopters, stand-off-weapons, drones.

'Approach and Landing': locating, approaching, and bringing the aircraft safely down on a runway not only on dedicated safe airports but also in the 'Forward Operating Strip' under military conditions or in airfields with low intense hostile environment like the UN protection zones.

The following definitions are in accordance with AGARD-AR-343.

'Dependability': The dependability is the aggregate term for reliability, availability, integrity (safety and security), and survivability. It is normally used only in a qualitative sense because the component measures are so diverse. To be used in a quantitative sense, dependability would have to include the numeric values for each of its component measures.

'Survivability': The survivability is the ability of a device to withstand the hazards created by any external hostile action. It is usually defined as the probability that the device will not suffer service degradation below a specified limit within a specified time period. This time period is usually one mission time, but sometimes it is specified on a per-hour basis.

'Reliability': The reliability is defined by a mathematical function, R(t), which evaluates the probability that a device will have provided acceptable service from some initial time until time = t.

Remark: This definition is comparable to RTCA DO 217 where acceptable service relates to the fact that the device / function has no failure.

The following definitions are in accordance with RTCA DO 217 Appendix L.

'Availability': The availability of a navigation system is the ability of the system to provide the required guidance at the initiation of the intended operation. Availability Risk: is the probability that the required guidance will not be present at the initiation of the intended operation. Availability is an indication of the ability of the system to provide usable service within the specified coverage area. Signal Availability: is the percentage of time that navigational signals transmitted from external sources are available for use. Availability is a function of both the physical characteristics of the environment and the technical capabilities of the transmitter facilities.

'Continuity': The continuity of a system is the ability of the total system (comprising all elements necessary to maintain aircraft position within the defined airspace) to perform its function without non-scheduled interruptions during the intended operation. The Continuity Risk is the probability that the system will be unintentionally interrupted and not provide guidance information for the intended operation. More specifically, continuity is the probability that the system will be available for the duration of a phase of operation, presuming that the system was available at the beginning of that phase of operation.

'Integrity': The integrity of a system is that quality which relates to the trust which can be placed in the correctness of the information supplied by the total system. Integrity Risk: is the probability of an undetected (latent) failure of the specified accuracy. Integrity includes the ability of the system to provide timely warnings to the user when the system should not be used for the intended operation.

8 FIGURES

See next page

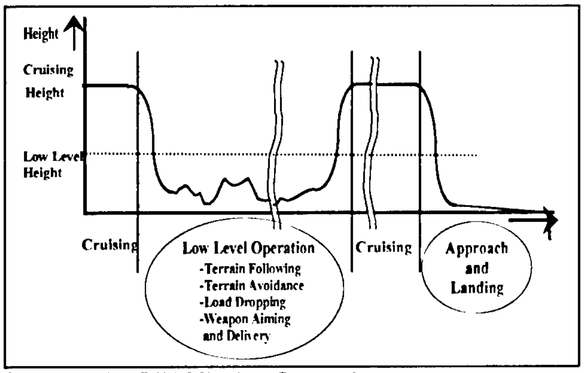


figure: 1 RAPIN Mission Scenario

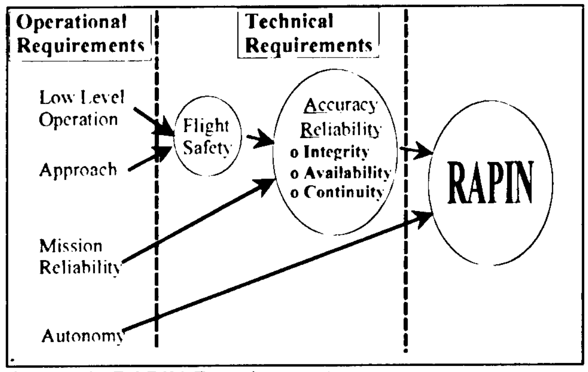


figure: 2 RAPIN Requirements

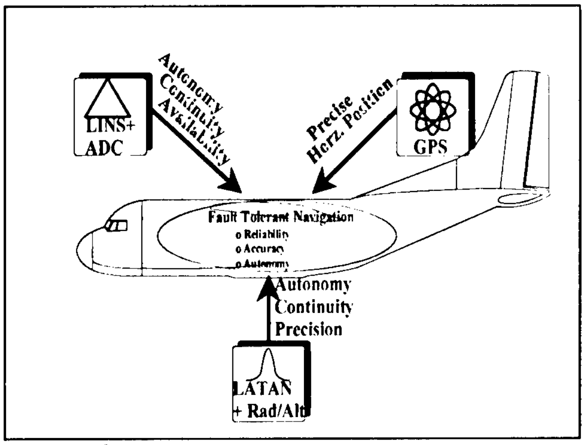


figure: 3 Sensor Integration

		LINS +Baro.	LATAN + R/A	GPS/DGPS	RAPIN
	Autonomy	high	high	medium / low	high
Reliability	Integrity	medium	medium	medium / high	high
	Availability	high	medium	medium	high
	Continuity	high	high	low	high
Accuracy	Horz. Pos.	short term: high long term: medium	medium	high	high
	MSL	medium	high	medium	high
	HGL	_	high	_	high

figure: 4 Sensor Characterisation

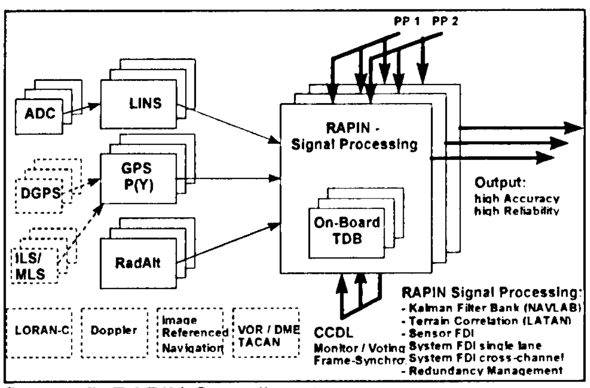


figure : 5 RAPIN Overall system

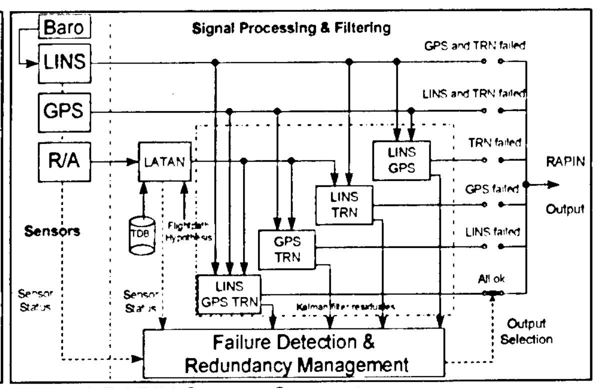


figure: 6 RAPIN System Concept

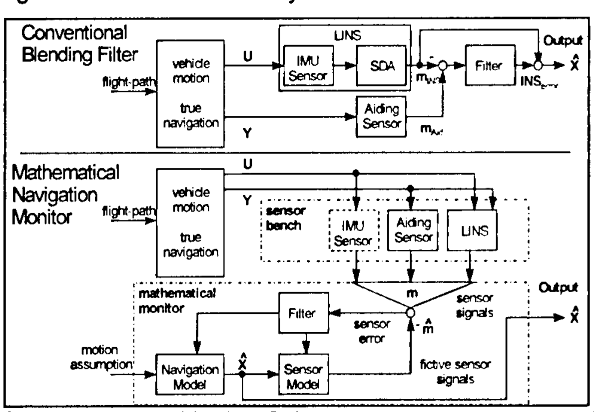


figure: 7 RAPIN Monitor Scheme

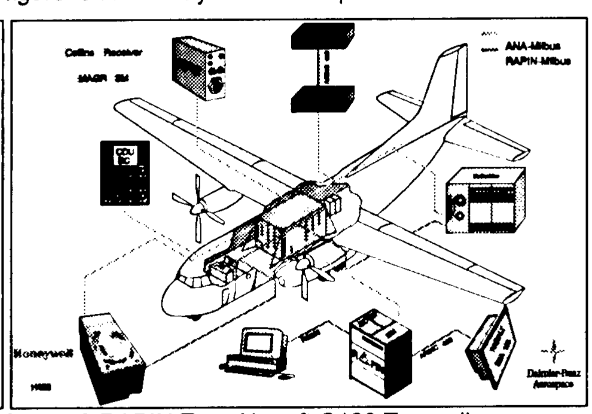


figure: 8 RAPIN Test Aircraft C160 Transall

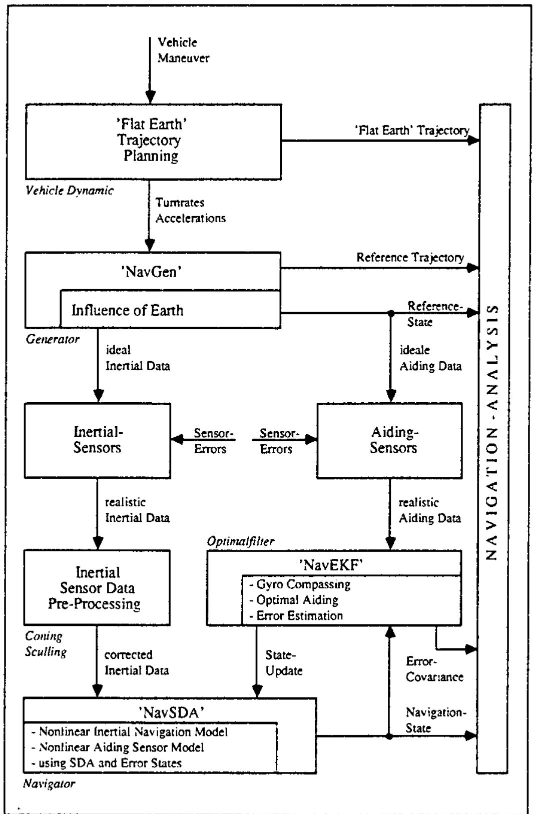


figure 9: NavLab Overview

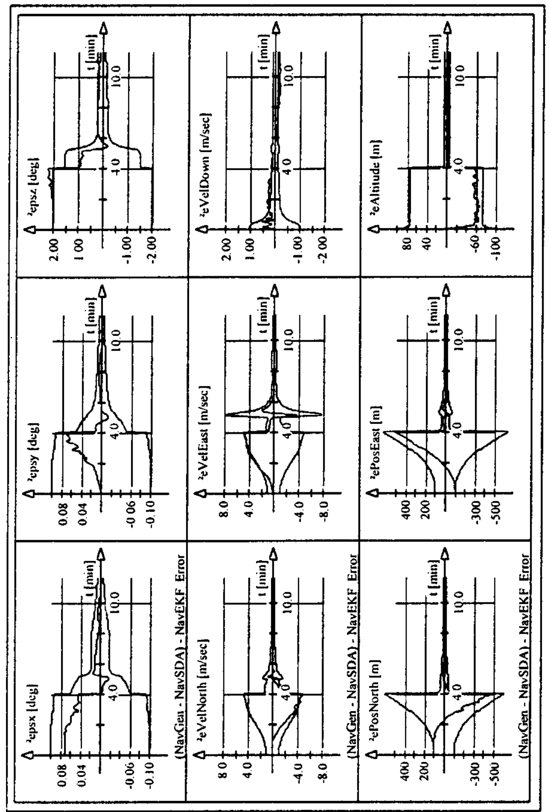


figure 10: NavLab Simulation

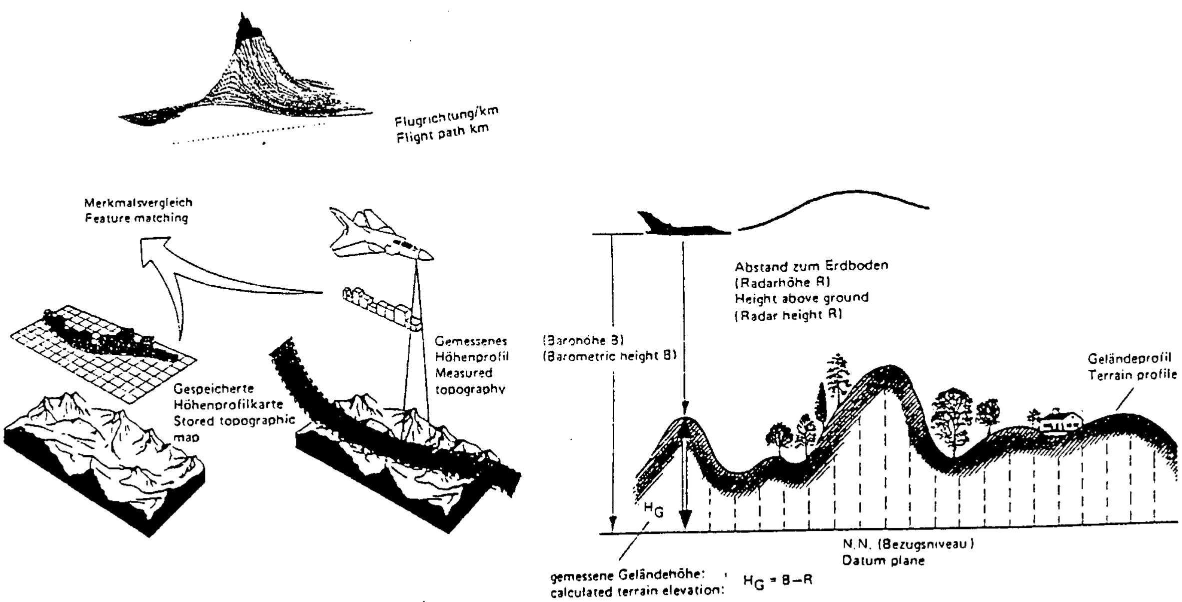


figure 11: LATAN TRN Principle

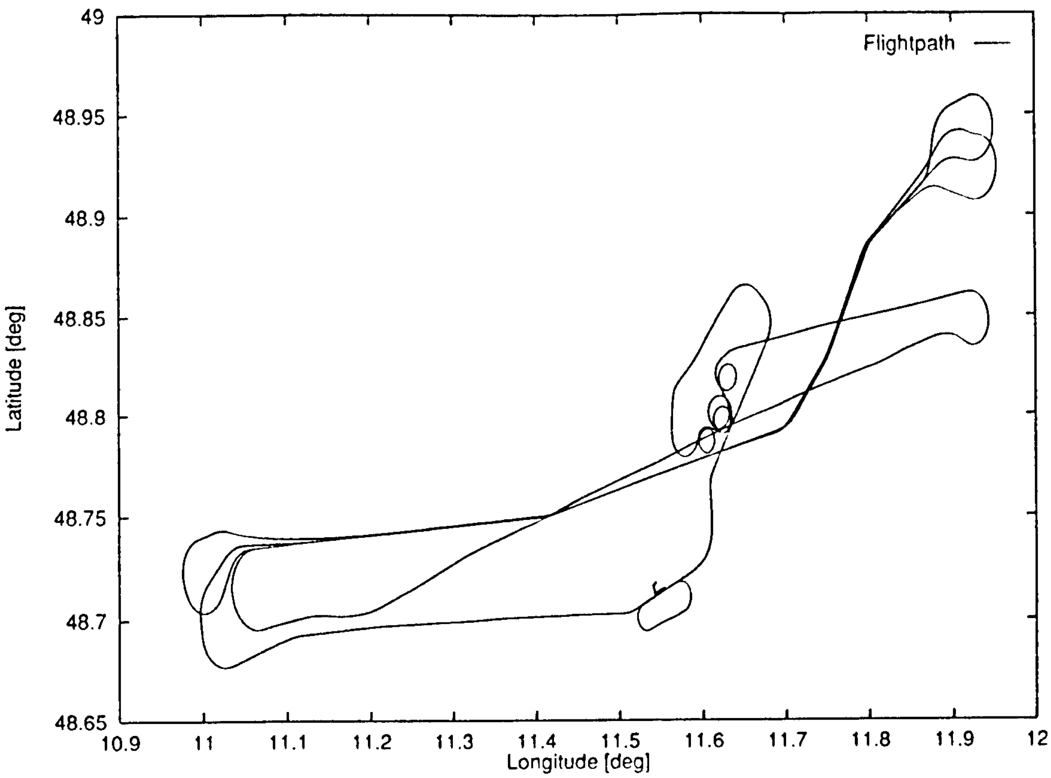


figure 12: Horizontal Flight Trajectory

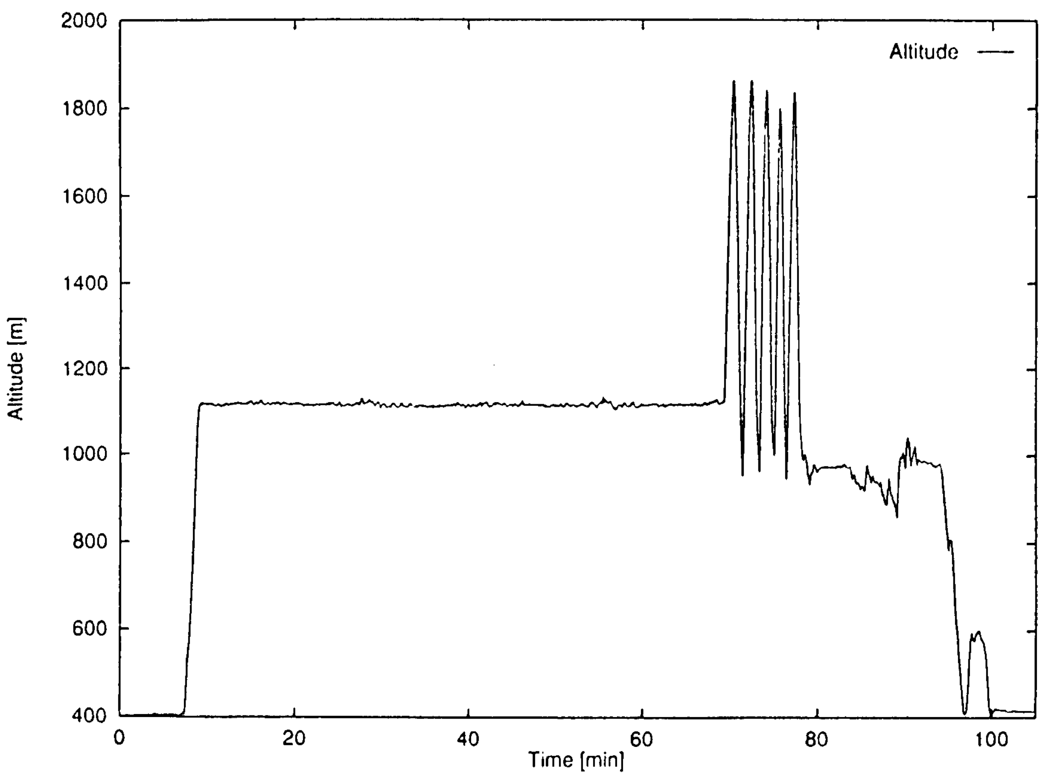


figure 13: Vertical Flight Trajectory

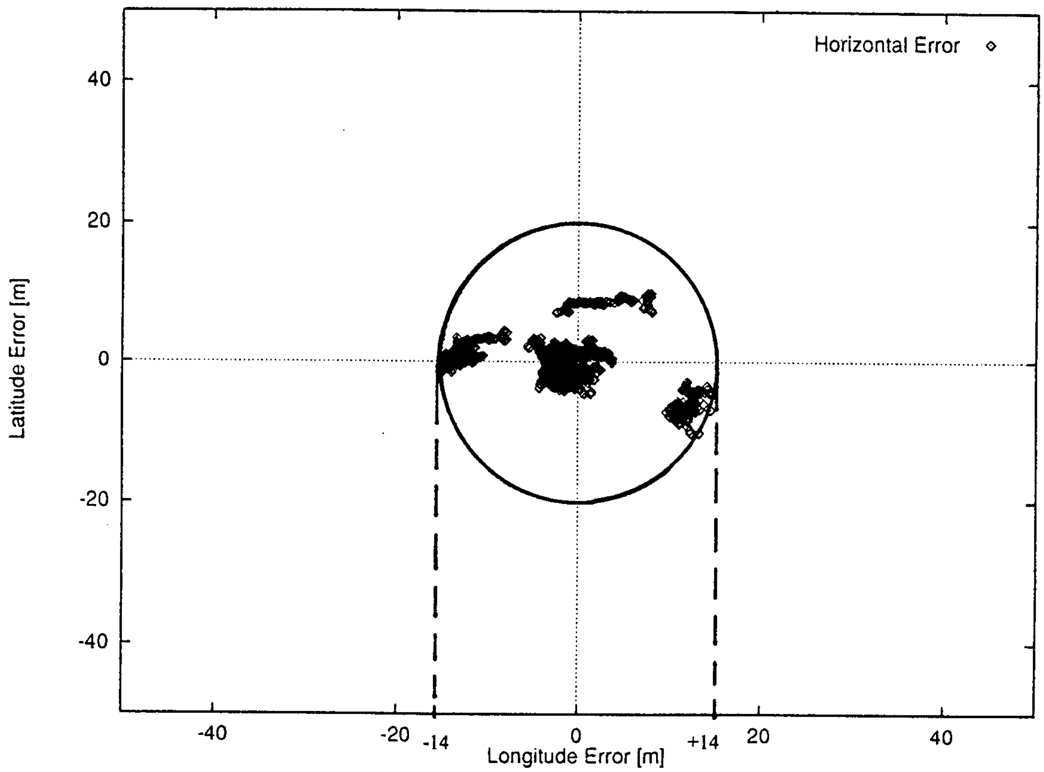


figure 14: Horizontal Navigation Error

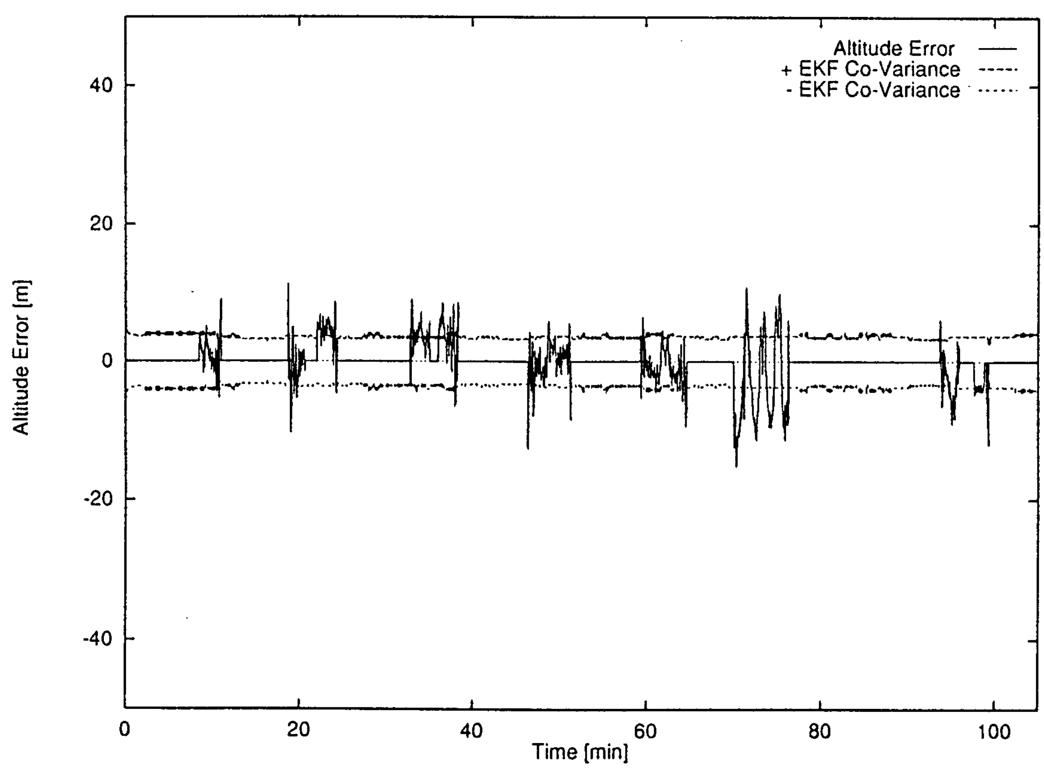


figure 15: Vertical Position Error

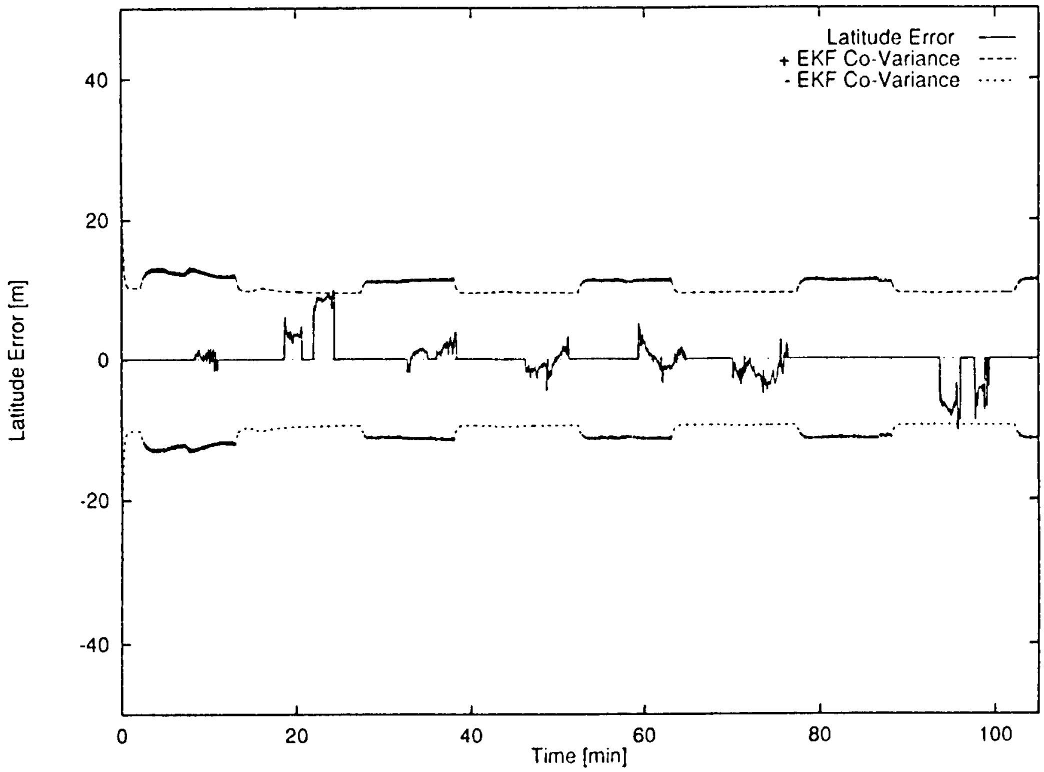


figure 16: Latitude Position Error

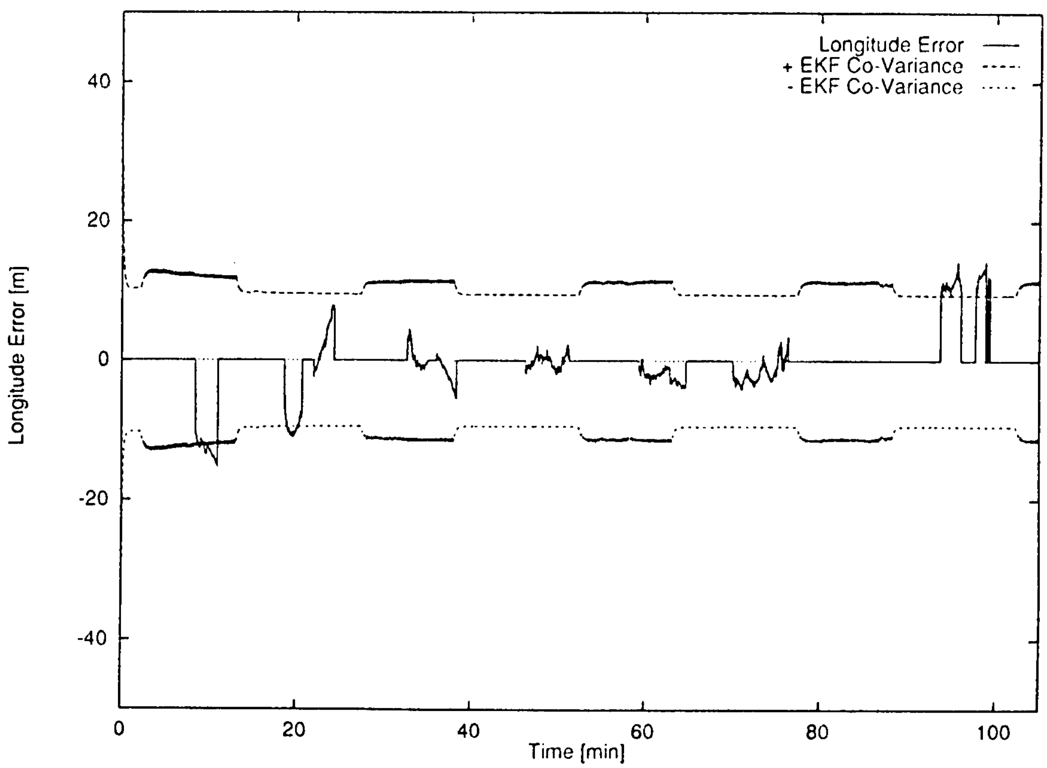


figure 17: Longitude Position Error

Landmark navigation and autonomous landing approach with obstacle detection for aircraft

Simon Fürst[a], Stefan Werner[a], Dirk Dickmanns[b], Ernst-Dieter Dickmanns[a]

[a]Institut für Systemdynamik und Flugmechanik, Universität der Bundeswehr München
[b]Institut für Technik intelligenter Systeme
Werner-Heisenberg-Weg 39, D-85577 Neubiberg

ABSTRACT

A machine perception system for aircraft and helicopters using multiple sensor data for state estimation is presented. By combining conventional aircraft sensors like gyros, accelerometers, artificial horizon, aerodynamic measuring devices and GPS with vision data taken by conventional CCD-cameras mounted on a pan and tilt platform, the position of the craft can be determined as well as the relative position to runways and natural landmarks.

The vision data of natural landmarks are used to improve position estimates during autonomous missions. A built-in landmark management module decides which landmark should be focused on by the vision system, depending on the distance to the landmark and the aspect conditions. More complex landmarks like runways are modeled with different levels of detail that are activated dependent on range. A supervisor process compares vision data and GPS data to detect mis-tracking of the vision system e.g. due to poor visibility and tries to reinitialize the vision system or to set focus on another landmark available. During landing approach obstacles like trucks and airplanes can be detected on the runway.

The system has been tested in real-time within a hardware-in-the-loop simulation. Simulated aircraft measurements corrupted by noise and other characteristic sensor errors have been fed into the machine perception system; the image processing module for relative state estimation was driven by computer generated imagery. Results from real-time simulation runs are given.

Keywords: machine perception, computer vision, autonomous aircraft, hardware-in-the-loop simulation, landmark navigation, obstacle detection.

1. INTRODUCTION

The extended machine perception system (MPS) presented in this paper has been designed to perform autonomous and automatic aircraft or rotorcraft flights [1]. A complete mission from take-off to landing has to be conducted. For this purpose, the system has to have the capabilities to estimate the actual state of the aircraft, to navigate according to the mission waypoints, and to stabilize and guide the aircraft. For full autonomy only sensors mounted onboard the aircraft are being used, i.e. no precision navigation aids with ground-based infrastructure are included.

Optimal state estimation is achieved by combining standard aircraft sensors which provide good information in the high frequency range with an image processing system (IPS), which provides good information at lower frequencies and a very high accuracy during the final landing approach.

The runway obstacle detection and tracking (RODT) module is part of the IPS and can detect obstacles like trucks on the runway. When an obstacle gets detected an alert is sent to the MPS in order to break off the landing approach.

Section 2 describes the process structure of the MPS and the IPS to conduct autonomous and automatic helicopter flight from lift-off along a pre-defined flight path towards a landing spot.

Section 3 explains the hardware implementation designed for hardware-in-the-loop simulation and real flight tests.

Section 4 focuses on results from real-time simulation trials. A horizontal flight loop and a landing approach with obstacle detection will be discussed.

Section 5 gives some conclusions and an outlook on further developments.

2. PROCESS AND DATA STRUCTURE OF THE MPS AND THE IPS

The machine perception system presented here consists of the following basic processes:

Further author information:
S.F.: Email: simon.fuerst@unibw-muenchen.de; WWW: http://www.unibw.muenchen.de/campus/LRT/LRT13;
Telephone: +49-89-6004-3580; Fax: +49-89-6004-2082

Paper presented at the AGARD MSP Symposium on "System Design Considerations for Unmanned Tactical Aircraft (UTA)", held in Athens, Greece, 7-9 October 1997, and published in CP-594.

- the multi-sensor state estimator (MSSE)
- the vehicle control process (VC)
- the aircraft interface process (AC-IF)
- the interface process to the image processing system (IPS-IF).

The image processing system consists of the following basic processes:
- the model based landmark tracking process (REALIS)
- the runway obstacle detection and tracking process (RODT)
- the TIP-Bus processes (TIP)
- the interface process to the machine perception system (MPS-IF)

The processes and their communication data paths are shown in Fig. 2.1.
The processes and the data structure of the MPS had already been extensively discussed in [1]. So in this paper only a brief review of the MPS will be given, but the IPS will be discussed in detail.

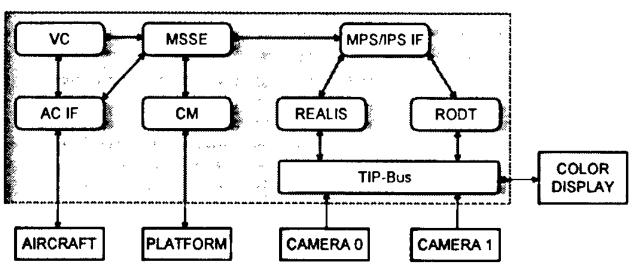


Figure 2.1: Processes and data paths of the MPS and IPS.

2.1 Multi-sensor state estimator

The multi-sensor state estimator uses measurements from several sensor processing modules to generate the optimal state estimate. The state vector of the MPS consists of the state variables shown in equation 2.1; they are related to a body-fixed coordinate system located in the craft's center of gravity and pointing along the main axes of moments of inertia, and a geographic coordinate system.
An Extended Kalman Filter [8] is implemented to perform recursive state estimation. State prediction is done by exploitation of either a non-linear dynamical model of a BO105 helicopter or an integration model.
All sensor processing modules attached to the multi-sensor state estimator receive a predicted state and the related error covariance matrix; they return valid measurements in the given structure. As a result, the state estimate update does not need to have any knowledge about the sensors themselves; this knowledge is stored in the sensor processing modules.

$$\mathbf{x} = \begin{bmatrix} a_x \\ u \\ u_w \\ a_y \\ v \\ v_w \\ a_z \\ w \\ w_w \\ p \\ q \\ r \\ \phi \\ \theta \\ \psi \\ \lambda \\ \varphi \\ h \end{bmatrix} = \begin{bmatrix} \textit{longitudinal body - related acceleration} \\ \textit{longitudinal inertial speed component} \\ \textit{wind speed} \\ \textit{latitudinal body - related acceleration} \\ \textit{latitudinal inertial speed component} \\ \textit{wind speed} \\ \textit{vertical body - related acceleration} \\ \textit{vertical inertial speed component} \\ \textit{wind speed} \\ \textit{rotation rate about } x - \textit{axis} \\ \textit{rotation rate about } y - \textit{axis} \\ \textit{rotation rate about } z - \textit{axis} \\ \textit{roll angle} \\ \textit{pitch angle} \\ \textit{yaw angle} \\ \textit{geographid atitude} \\ \textit{geographic longitude} \\ \textit{height above Earth ellipsoid} \end{bmatrix} \qquad (2.1)$$

2.2 Vehicle control

Vehicle control performs the navigation task, monitors the actual state of the mission and computes the controls for automatic flight. Currently, a state controller is implemented combining feedforward and feedback components; more information about that may be found in [1] and [2].

2.3 Aircraft interface

The aircraft interface process receives measurement data from the aircraft onboard computer and transmits control values received from the vehicle control process in the case of automatic flight. State estimates from the multi-sensor state estimator are used to compute predicted measurements, the corresponding Jacobian vectors, which are the derivatives of the measurements related to the state vector, and confidence values, which are used to determine sensor faults for outlier removal.
The simulated measurements are corrupted with noise and other characteristic sensor errors [7]. Currently, accelerometers, rate gyros, artificial horizon, barometric height, aerodynamic data and GPS measurements in S/A-mode are simulated.

2.4 MPS / IPS interface

The image processing interface process receives state estimates from the multi-sensor state estimator. They are used to perform the selection of objects to be surveyed by the image processing system. Location information and window parameters of specific objects stored in a database determine if an object is detectable. If the object is

close enough and lies within the sweeping area of the pan and tilt platform, a command is sent to the platform controller consisting of the angles required to point towards the object. If no object is within reconnaissance range, the platform is directed towards the horizon.

After a short time interval, a message is sent to the image processing system consisting of the actual camera platform angles, the predicted state estimate and the objects to be surveyed. The image processing system starts a state estimation process with these initial values and sends the current state estimates back to the image processing interface process. Similar to the aircraft interface process, a confidence match is performed; if the state estimates stemming from the image processing system are regarded to be out of the confidence range, the image processing system is reset.

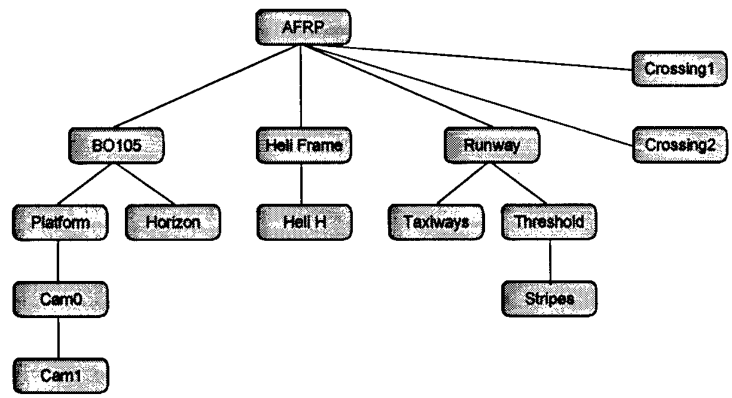


Figure 2.2: Scene tree of the landmark tracking system.

2.5 Landmark tracking

The landmark tracking system is based on REALIS which is a model based object tracking system that has been developed for the ROTEX free-flyer experiment during the D2-Spacelab-mission [3].

The REALIS system consists of four major parts:

- **Object modeling**

  The three dimensional geometry of objects is set up by points, edges and surfaces. For all these elements homogenous coordinates are used exclusively. When an object geometry is created its points get connected to edges and the edges get connected to closed surfaces. Ferguson curves are used for modeling edges as they only require tangent parameters to describe a general curve in 3D space.

  Every edge of an object has an indicator whether it should be used for image measurement or not. The horizon, for example, is modeled as a huge rectangle perpendicular to the surface of the Earth with only one edge visible. Furthermore whole objects may be enabled and disabled for image measurement via the MPS-IF. This is an easy way to implement multiple levels-of-detail (LOD) for one object. The object 'runway' for example has been modeled as a rectangle on the coarse level, with its adjacent taxiways on the 2nd, the outline of both thresholds on the third, and the single rectangular patches of the thresholds on the fourth level.

- **Scene tree**

  All objects are linked together in a tree structure which is shown in figure 2.2. Each node, i.e. object has its own local coordinate system. The positions of all son-nodes are given in local coordinates of their unique father's coordinate system. As in a tree there is always exactly one path from one node to another; the relative positions between all objects are described uniquely. The relative position between two nodes can either be fix or will be estimated.

  As root node the airfield reference point (AFRP) of the airport Braunschweig / Germany was chosen. The x-axis of this root coordinate system is pointing north, the y-axis is pointing to the east and the z-axis is pointing to the center of gravity.

- **Image measurement**

  Image measurement starts with making a visibility test for all object surfaces. Therefore, the normal vector of each surface is calculated and when it is pointing towards the camera the surface is called 'visible'. Then the homogenous coordinate transformation matrices have to be build. This is done by walking through the scene tree from the present object to the active camera and multiplying all local transformation matrices. Now the edges of the objects can be transformed into the image coordinate system, and measurement commands for the feature extraction library 'Cronos' [5] can be generated.

- **State estimation**

  An extended Kalman Filter [8] is used to estimate all state variables. This is a recursive process performed in two steps:

  Prediction of the state vector and the covariance matrix:

$$\mathbf{x}^{*} = \Theta \cdot \hat{\mathbf{x}} + \mathbf{B} \cdot \mathbf{u}$$

$$\mathbf{P}^{*} = \Theta \cdot \hat{\mathbf{P}} \cdot \Theta^{T} + \mathbf{Q}$$

  For state prediction a simple integration model is used.

  Innovation of the Kalman-gain, the covariance matrix and the state vector:

$$\mathbf{K} = \mathbf{P}^{*} \cdot \mathbf{C}^{T} \cdot (\mathbf{C} \cdot \mathbf{P}^{*} \cdot \mathbf{C}^{T} + \mathbf{R})^{-1}$$
$$\hat{\mathbf{P}} = (\mathbf{I} - \mathbf{K} \cdot \mathbf{C}) \cdot \mathbf{P}^{*} \qquad (2.3)$$
$$\hat{\mathbf{x}} = \mathbf{x}^{*} + \mathbf{K} \cdot (\mathbf{y} - \mathbf{y}^{*})$$

The Jacobian matrix C describes the relation between measurements and state variables. It is a function of object geometry, its position relative to the camera and the camera parameters like focal length and resolution.
The measurement variance matrix R is constant and contains the characteristic sensor errors.
After REALIS has been started via the MPS-IF it runs autonomously at a cycle time of 20ms and processes the two camera images sequentially. The current state estimate of the aircraft as shown in equation 2.4 is send back to the MPS every 40ms and the camera platform angles get updated from the MPS.

$$\mathbf{x} = \begin{bmatrix} a_x \\ u \\ x \\ a_y \\ v \\ y \\ a_z \\ w \\ z \\ \dot{p} \\ \dot{q} \\ \dot{r} \\ p \\ q \\ r \\ \phi \\ \theta \\ \psi \end{bmatrix} := \begin{bmatrix} \textit{body-related longitudinal acceleration} \\ \textit{corresponding speed component} \\ \textit{position} \\ \textit{body-related lateral acceleration} \\ \textit{corresponding speed component} \\ \textit{position} \\ \textit{body-related vertical acceleration} \\ \textit{corresponding speed component} \\ \textit{position} \\ \textit{rotational acceleration about } x-\textit{axis} \\ \textit{rotational acceleration about } y-\textit{axis} \\ \textit{rotationnl acceleration about } z-\textit{axis} \\ \textit{rotation rate about } x-\textit{axis} \\ \textit{rotation rate about } y-\textit{axis} \\ \textit{rotation rate about } z-\textit{axis} \\ \textit{roll angle} \\ \textit{pitch angle} \\ \textit{yaw angle} \end{bmatrix} \qquad (2.4)$$

2.6 Runway obstacle detection and tracking

The runway obstacle detection and tracking system is based on algorithms used for the detection of cars driving on a road [4]. The known area of the runway is scanned along horizontal search paths for small edge elements. If there is a local accumulation of edge elements found they are aggregated to an object outline. If the area of this new object is of valid size and shape for a truck and its gray level differs from the mean gray level of the white markings on the runway an obstacle is found. When this detection can be repeated for at least 5 video cycles an obstacle alert is sent to the MPS.

2.7 Image acquisition and distribution with the TIP-bus

The transputer image processing (TIP) bus is a fast backbone for transferring video images in real time. It will be explained in more detail in section 3. The process running on the monochrome frame grabber (MFG) is the TIP-Bus master. It controls image acquisition and distribution whereas the other TIP processes are slaves that receive images.
Two standard monochrome TV cameras are connected to the input of the MFG. As TV cameras have interlaced images the input selector of the MFG switches between camera 0 and camera 1 while field 0 and field 1 are digitized. Therefore, a new image with a reduced resolution of 320 × 256 pixel but with no delay time between the lines is available every 20ms. The processes running on the TIP-slaves use double buffering for measurement input and for drawing images for monitoring. The images to be drawn will be sent to a display process that is connected to a color graphics display for real time visualization of the results of the image processing system.

3. HARDWARE IMPLEMENTATION

The whole system is implemented on a parallel transputer system developed by Parsytec. Each transputer offers four high speed communication links with a band width of 20Mb/s and a minimum overlay time for communication setup. As standard processors the inmos T805/30MHZ have been chosen. For the 'number crunching' tasks like state estimation and image processing Motorola's PowerPC 601 with 66MHz respectively 80MHz is used. The MPS processes are running at a cycle time of 40ms, the IPS processes are running even at 20ms.
The hardware implementation as shown in figure 3.1 consist of three main parts:

3.1 Machine perception system

The MSSE module performing the multi-sensor state estimation is placed on a PowerPC 601; it is connected to the VC module performing the vehicle control process and the AC-IF module running the aircraft interface process, both placed on T805 transputers. The communication module CM is implemented to manage the data exchange with the camera platform controller. The MPS / IPS-IF handles the data flow between the MSSE and REALIS respectively RODT.
The connection to the simulation computer is realized by a RS422 link with the same data exchange structures as specified for future flight test.

3.2 Image processing system

Real time images are transferred via the TIP-Bus developed by Parsytec. It is a 32Bit bus running at 25MHz with a maximum transfer rate of 100MBs. The processes running on the TIP boards carry out the slightly complicated initialization of the TIP-Bus and, in the real-time phase, they take care of the correct sending and receiving of the images.

Two monochrome TV cameras with focal lengths of 25mm and 50mm are connected to the TIP-MFG. Digitizing of the camera signals is controlled by the MFG process running on a T805. The TIP-MPCs have 2MB of triple ported VRAM. The TIP-Bus controller process runs on the T425 that is also used by the PPC 601 for communication purposes. REALIS and RODT are both running on a PPC 601 of their own, so that they have direct access to the camera images and a maximum of computing power available. They are both connected to the IP-IF via a direct link. The TIP-CGD has a video controller that displays the contents of its VRAM on a standard VGA monitor. So the image draw buffers receive from the TIP-MPCs can be displayed or saved on a VCR. The process running on the T805 mounted on the TIP-CGD can save images as PCX files in the real-time phase.

3.3 Camera platform controller

The camera platform controller receives the position commands from the MPS and sends back the current yaw and pitch angle of the platform. The digital controller runs at a cycle time of 2ms and stabilizes the platform inertially by the use of two rate gyro signals.

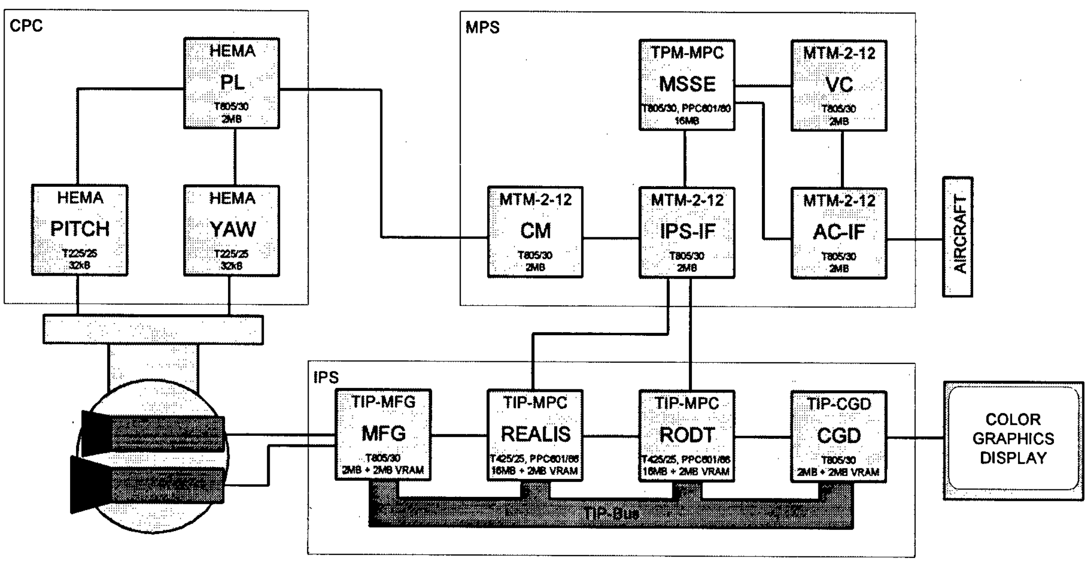


Figure 3.1: Hardware architecture of the system.

4. RESULTS FROM SIMULATION TRIALS

Several closed-loop simulation trials with a BO105 helicopter have been conducted under real-time conditions at a cycle-time of 40ms. The simulation environment was a model of the Braunschweig airport region [2]. The upper part of the snap-shots is the output of the weak tele camera (25mm), the lower part stems from the stronger tele-lens camera (50mm); the two-axis platform was engaged during the approach. Within the images the outlines of the currently active landmarks are drawn. They represent the internal estimate of the IPS about the relative position of the helicopter. The short lines mostly perpendicular to the outlines are the search paths of the edge detectors.

4.1 Horizontal flight loop

The flight plan of the go-around trip in the region of the Braunschweig airport with all its way-points and landmarks is shown in figure 4.1. The helicopter lifted-off at the point called 'Heli H East' and passed the first way-point 'Threshold 27' at a height of 30m and a speed of 20m/s. On the way to the next way-point 'Threshold 09'the snap-shots shown in figure 4.2 to 4.4 have been taken. These figures show the different LODs of the runway-model. The next way-point called 'Crossing 1' is about 3km west of the runway. During this flight period at a speed of 30m/s in a height of 60m the IPS was set inactive and the MPS accumulated an

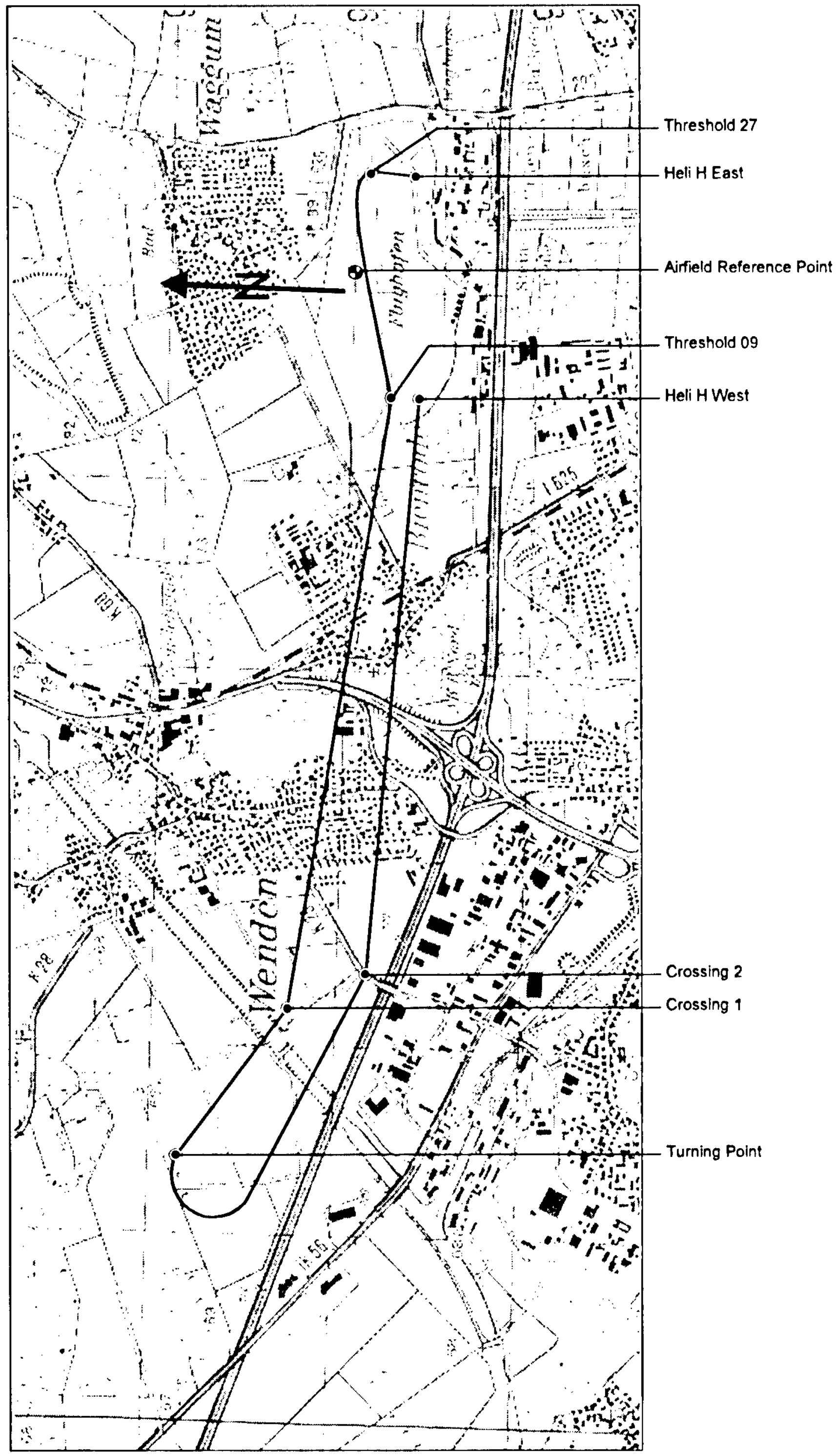


Figure 4.1: Flight plan of the circular flight test in Braunschweig.

error in the position estimate as GPS was used in S/A mode. When the IPS started tracking the 'Crossing 1' (fig. 4.5) the position accuracy could be increased significantly. After flying a sharp curve at the 'Turning Point', 'Crossing 2' was the next landmark (fig. 4.6). The flight loop ended with a successful landing approach on the 'Heli H West'. At a distance of 600m tracking of the taxiways was started; at a distance of 150m the frame and the white 'Heli H' were also used for tracking.

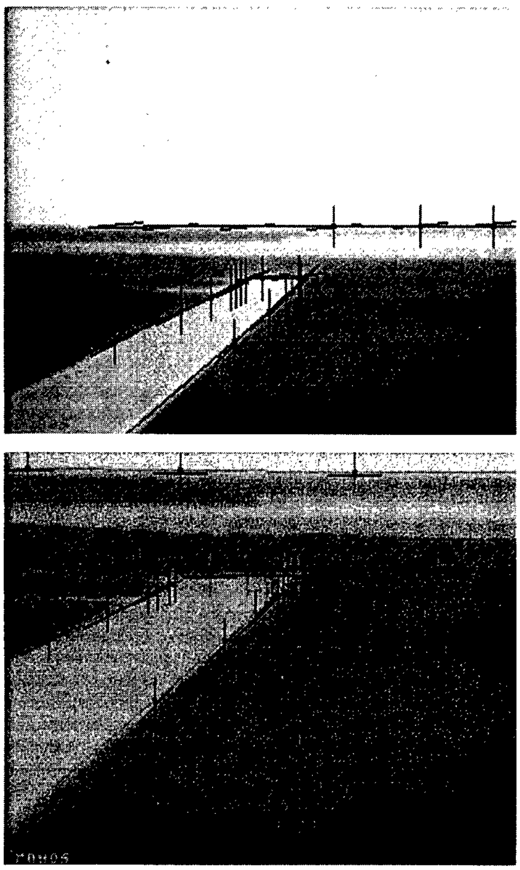
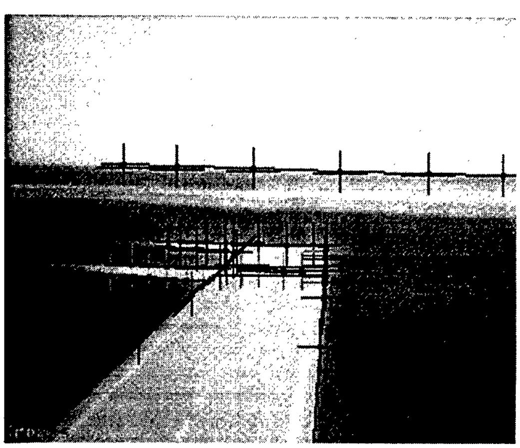


Figure 4.2: Runway at lowest LOD as a rectangle.



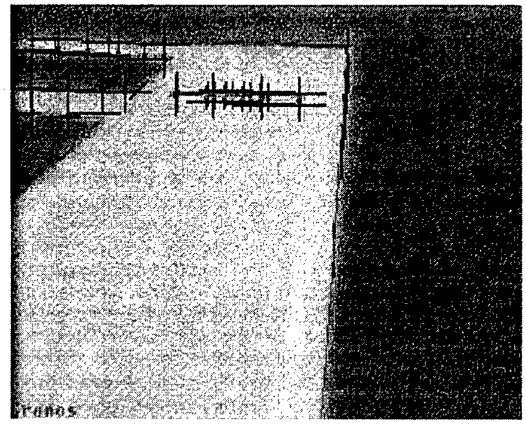


Figure 4.3: Runway and taxiways active; threshold had just been activated.

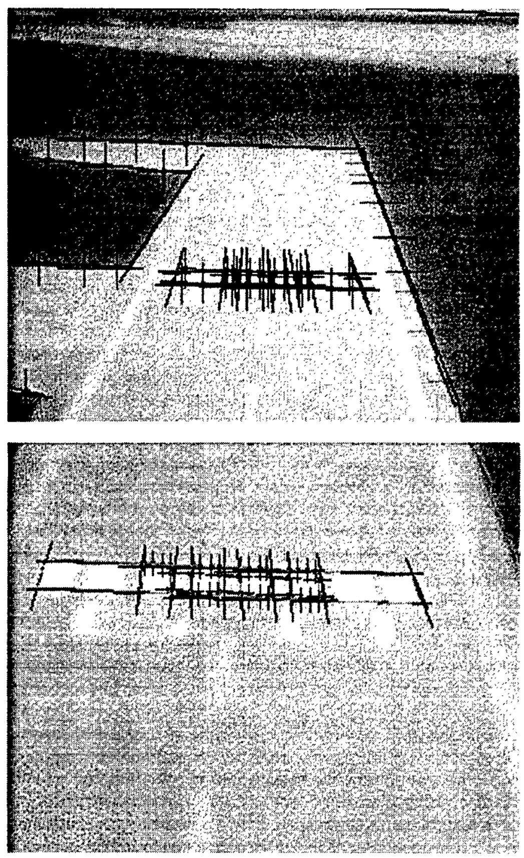
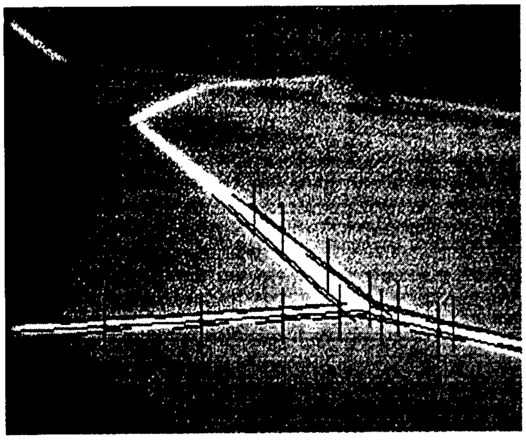


Figure 4.4: Low altitude fly-by at 'Threshold 09' with all LODs active.



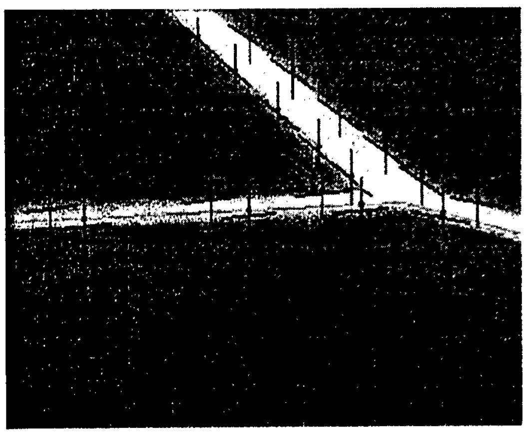
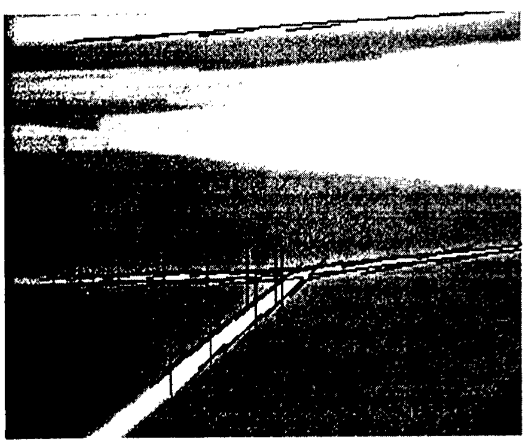


Figure 4.5: Tracking of 'Crossing 1' with the position error estimate still decreasing.



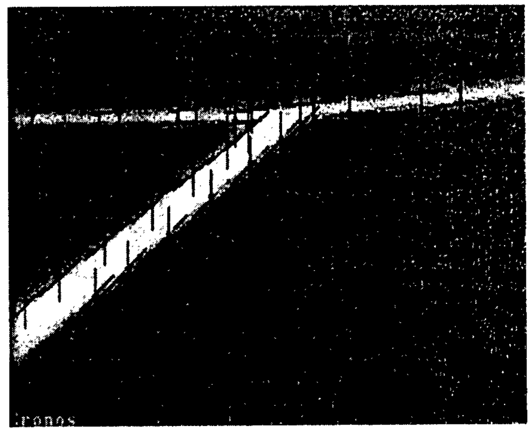
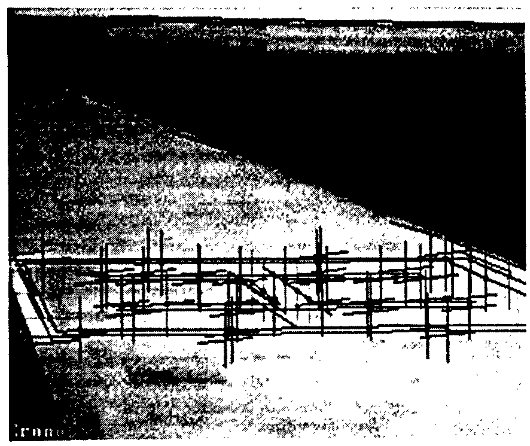


Figure 4.6: Tracking of 'Crossing 2' with the village of Wenden in the background.



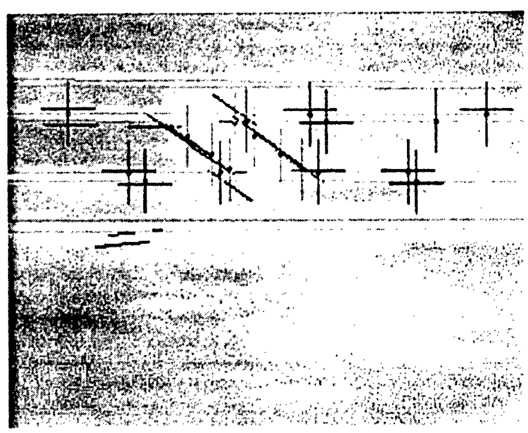


Figure 4.7: Tracking of taxiways, frame and Heli H during the final approach.

In the next three subsections timeplots from the flight loop are discussed. The figures show the longitudinal and lateral position of the aircraft plotted over the time axis. The lines marked 'TRUE' correspond to the states calculated by the simulation computer. The lines marked 'MPS' present the states estimated by the MSSE that are derived from conventional sensors and the IPS. The

'IPS' lines correspond to the state estimated by the image processing system that runs independently after activation. The 'GPS' lines are the simulated GPS signals with C/A code and selective availability. This signal has a 1Hz refresh rate like common GPS receivers.

4.1.1 Measurement of the runway

The IPS was activated at 38s with the rectangular runway model. After a short time of oscillation the state estimate of the IPS comes very close to the real values, with a very good longitudinal estimate as there are more measurement windows on the sidelines than on the endlines of the runway. The stronger oscillation of the lateral estimate are eliminated when the taxiways get activated at 44s.

4.1.2 Measurement of crossing 2

The position estimates show oscillations when the IPS gets activated. Their amplitudes die away over a period of about 4s and converge on the real values. This effect can be traced back to the distribution of the measurement windows in this scene. The concurrent estimation of range, height and pitch angle is based on features of the horizontal road in fig. 4.6. These feature are very indistinct when the IPS gets started at a distance of 800m, but they become clearer as the aircraft approaches the crossing.

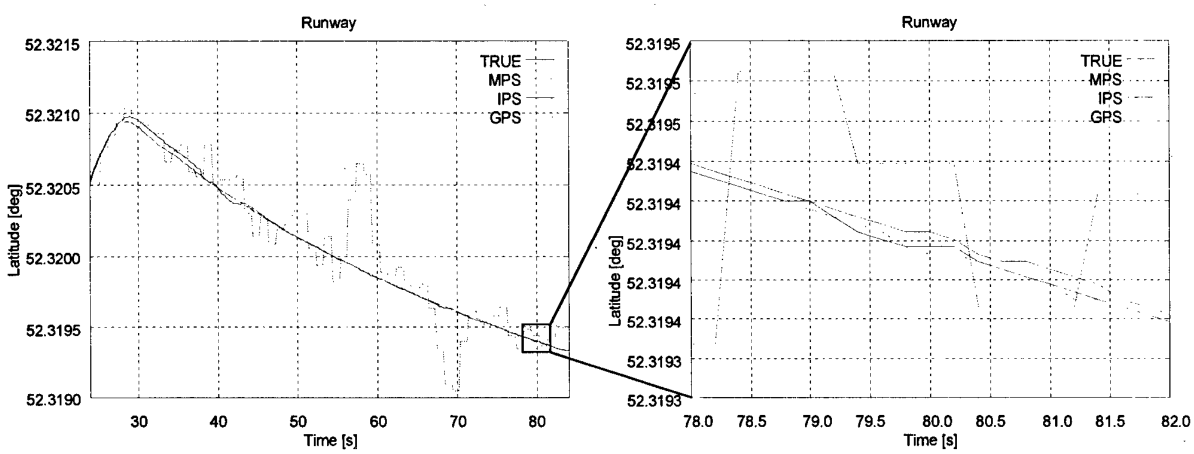


Figure 4.8: Latitude position of helicopter during runway fly-by.

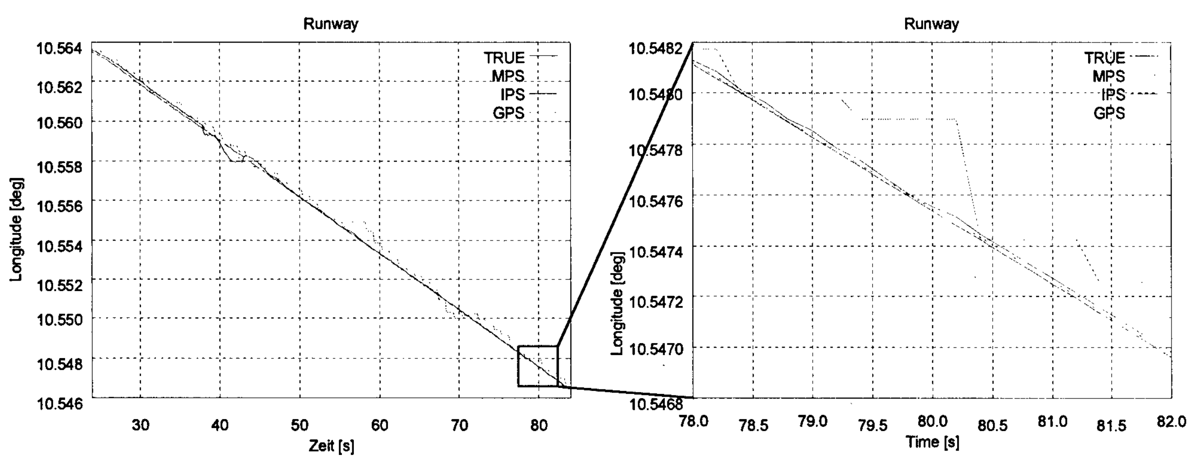


Figure 4.9: Longitude position of helicopter during runway fly-by.

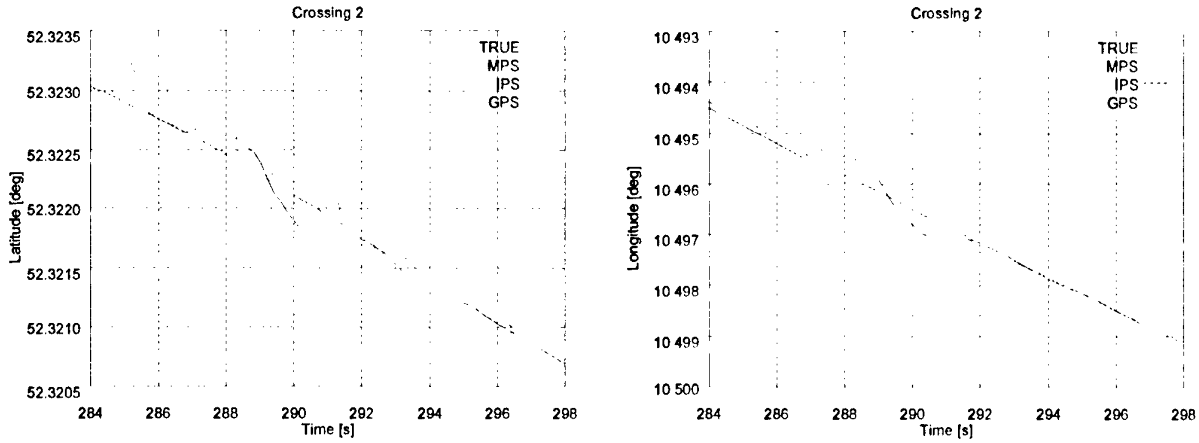


Figure 4.10: Latitude and longitude position of helicopter during crossing 2 fly-by.

4.1.3 Measurement of the helicopter landing spot

The aim of this flight was the western helicopter landing spot that is located on the taxiways. Tracking of the taxiways began in a range of 600m so that the position estimate got accurate enough to

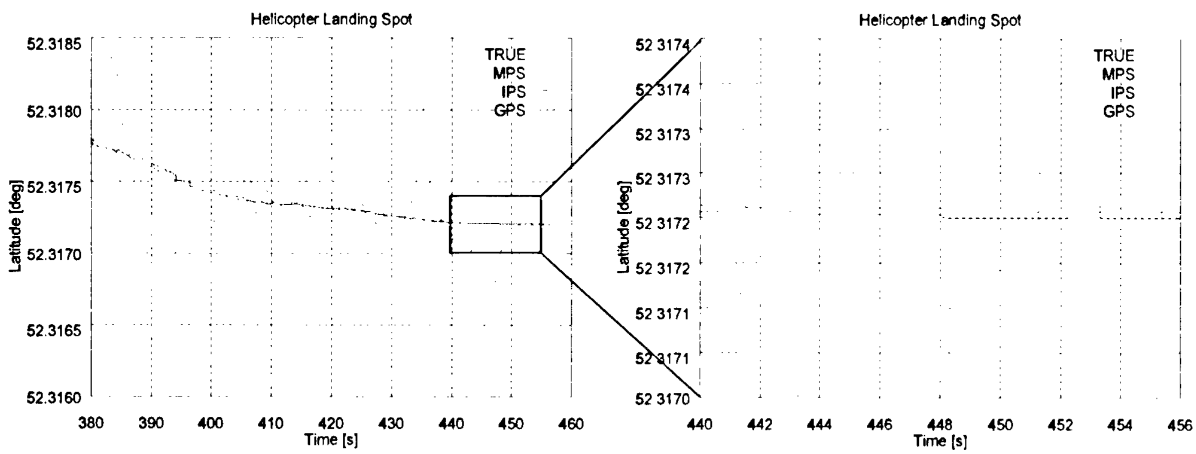


Figure 4.11: Latitude position of helicopter during final landing approach.

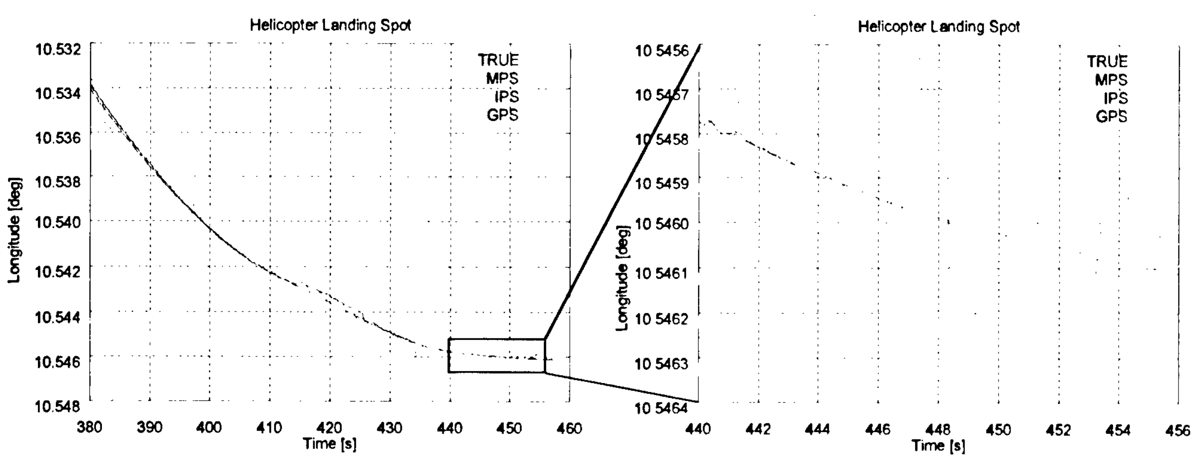


Figure 4.12: Longitude position of helicopter during final landing approach.

start tracking of the difficult object helicopter H and its frame in a range of 150m. In the final approach, the precision of the position estimate was below 0.5m.

4.2 Landing approach with obstacle detection

A straight landing approach of the BO105 helicopter at Threshold 09 was conducted to test the RODT module. Snap-shots are shown in Figure 4.13, where a truck, standing in longitudinal direction was used as an obstacle. At a distance of 2.1km it could be detected in the stronger tele camera and at a distance of 1.3km in the mild tele camera.

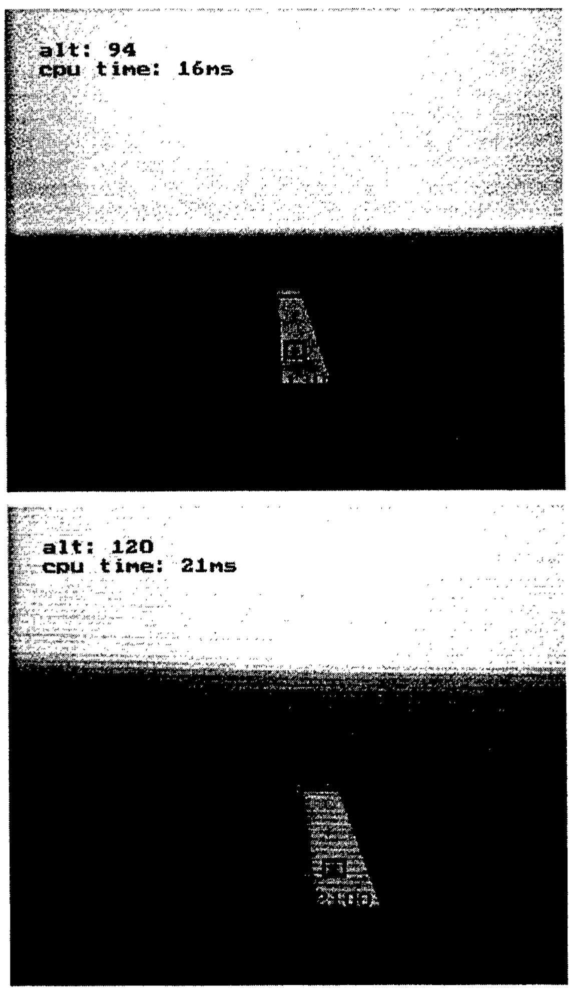


Figure 4.13: Obstacle detection during landing approach.

5. CONCLUSION

Results from real-time hardware-in-the-loop simulations for autonomous landmark navigation and landing approaches have been demonstrated. Image processing as a sensor for relative state estimation in combination with inertial sensors is able to deliver the accuracy required to perform precise automatic flight and landing guidance. Further developments we are working on are:

- Improvement of overall system performance by porting the algorithms to a new, more powerful and versatile hardware.
- Upgrading of the image generation system to get a more realistic image simulation at higher resolutions.
- Implementation of area based image operators.
- Development of a landmark and landscape database based on DTED and DFAD.

REFERENCES

1. S. Werner, S. Fürst, D. Dickmanns and E.-D. Dickmanns, "A vision based multi-sensor machine perception system for autonomous aircraft landing approach ", *Proc. SPIE AeroSense '96 Conf. on Enhanced and Synthetic Vision*, Orlando, FL, USA, 1996.
2. S. Werner, A. Buchwieser and E.-D. Dickmanns, "Real-time simulation of visual machine perception for helicopter flight assistance", *Proc. SPIE AeroSense '95 Conf. on Synthetic Vision for Vehicle Guidance and Control*, Orlando, FL, USA, 1995.
3. D. Dickmanns, "Knowledge Based Real-Time Vision". *Proc. 2nd IFAC Conf. on Intelligent Autonomous Vehicles '95*, Helsinki, 1995.
4. F. Thomanek, "Visuelle Erkennung und Zustandsschätzung von mehreren Straßenfahrzeugen zur autonomen Fahrzeugführung", Dissertation Universität der Bundeswehr München, Fakultät für Luft- und Raumfahrttechnik, München, Germany, 1995.
5. S. Fürst, "Cronos". Universität der Bundeswehr München, Institut für Systemdynamik und Flugmechanik, Internal Report 95-1, München, Germany, 1995.
6. F.-R. Schell, "Bordautonomer automatischer Landeanflug aufgrund bildhafter und inertialer Meßdatenauswertung", Dissertation Universität der Bundeswehr München, Fakultät für Luft- und Raumfahrttechnik, München, Germany, 1992.
7. R. Holland, "Digitale Verarbeitung von Flugversuchsdaten ohne Verwendung von Anti-Aliasing-Filtern am Beispiel eines Hubschraubers", *DFVLR-Mittelung 87-12*, Braunschweig, 1987.
8. A. Gelb (Ed.), "Applied Optimal Estimation",THE M.I.T. PRESS, Massachusetts Institute of Technology, Cambridge, MA, USA, 1984.

Integrated Data Link for UTA Applications: Design Considerations and Development Results

L. Bianchi, G. Battaini, G.L. Scazzola, E. Crovari
MARCONI S.p.A, Defence Division – Guided Systems
Via Negrone 1 A – 16153 GENOA
ITALY

1. ABSTRACT

The UTA (Unmanned Tactical Aircraft) or, in general, the UAV (Unmanned Air Vehicle) typical requirements for either non–lethal or lethal tactical missions, imply both the capability to transmit, by means of a Data Link, real–time data (for instance IR, Video, Radar or Navigation Data) and to receive commands (to reprogram partially or completely the mission profile) to / from Ground Stations.
The paper faces various aspects related to Data Links for UTA / UAV, presents system considerations and describes the development results obtained with the J Band UAV Data Link realized in Marconi and provided to Italian MoD.

2. INTRODUCTION

2.1 Scope of the document

Scope of the paper is to present some system considerations and design criteria for the Unmanned Air Vehicle's Data Links. These considerations and criteria will be derived both from theoretical evaluations of the UAV communication requirements and from experimental results achieved with a practical implementation of UAV Data Link, the Marconi SpA J Band Data Link.
To derive design criteria, the paper will briefly define the Data Links role and the UAV communication requirements to be fulfilled.
Starting from these requirements, considerations regarding the various typologies of Data Links for UAV applications (Point–to–Point Radio Data Links, Satellite Data Links, Fiber Optics Links) will be presented to identify the most suitable solutions.
The need of the Point–to–Point Radio Data Links for UAV applications, in particular for payload and Command&Control Data real–time transmission, will result.
A general design process to be followed in the development of UAV Data Links will then be presented.
As result of the test trials performed on the Marconi SpA J Band Data Link, the system and implementation choices derived during the design process have been verified and proved to be suitable for the UAV applications. The paper will present the experimental results achieved.
The last part of the paper focuses reader's attention on the additional functions that will be implemented in the near future for the Marconi applications and on the future developments foreseen for UAV Data Links.

2.2 Data link role in an Unmanned Air Vehicle

UAVs can be classified in families, e.g.:

* Tactical Military UAV for near real–time tactical reconnaissance , surveillance and target acquisition;
* Endurance Military UAV for near real–time theater intelligence and surveillance;
* UTA;
* Non–military UAV, tactical and endurance.

Possible UAV utilizations cover a wide range of applications like:

* **Military Environment:**
  - Surveillance;
  - Reconnaissance and Target Acquisition;
  - Targeting and Enemy Engagement;
  - Direct Attack;
  - Battle Damage Assessment;
  - Electronic Warfare;
  - Antisubmarine Warfare;
  - Amphibious Operation Support;
  - Training.
* **Non–Military Environment:**
  - Weather Monitoring;
  - Mapping / Monitoring of areas affected by disaster;
  - Search and Rescue;
  - Agricultural Support;
  - Border&Security Patrol;
  - Environment Monitoring.

Among all these UAV categories and for all these applications, main common Data Link functions can be identified in:

* Payload and combat system data transmission for "man–in the loop operations", real time analysis and data exploitation;
* Command / Control / Status signals transmission during navigation for near real time UAV control and monitoring;
* Command / Control / Status signal transmission during take–off / landing for real time UAV control and monitoring.

Other data link possible additional functions for specific operations are:

* Transmission relay for Over The Horizon communication;
* UAV tracking to allow precise determination of vehicle present position.

The design considerations presented in the paper are applicable to UTA but can be extended to all the main categories of UAVs.

The large majority of UAVs have one or more Data Links to perform the above required functions since a complete programmed mode, not in real–time, is generally not compatible with the above listed real–time applications and, furthermore, might not cope with Air Traffic Management Regulations, at present still in the definition phase.

UAV Data Links can be classified in the following main families:

* Point–to–Point and Broadcast Radio Links;
* Satellite Radio Links;
* Fiber optics links.
  Their use is possible for some specific applications, features some important advantages (OTH link, high data security,

Paper presented at the AGARD MSP Symposium on "System Design Considerations for Unmanned Tactical Aircraft (UTA)", held in Athens, Greece, 7-9 October 1997, and published in CP-594.

high bit rate, very low BER), but also some heavy disadvantages (low operational range, very high life cycle cost) which may limit their use.

Point–to–Point / Broadcast Radio Links and Satellite Radio Links will be addressed in the following sections.

3. DATA LINK REQUIREMENTS

For UAV Data Links, among the possible requirements, many depend on the specific application (for instance a military or a non–military application).

Nevertheless, in order to meet the interoperability constraints (e.g. different ground stations shall be able to communicate via the same point–to–point data link to different families of UAVs) and to reduce development and production costs, the Data Link architecture and structure should be, as much as possible, the same for the various users, with characterizations to be implemented in order to fulfill the specific application performance (e.g. different range or data rate).

For sake of clarity the main requirements have been split in three sets:

* Operational Requirements;
* Technical Requirements;
* Constructive Requirements.

3.1 Operational Requirements

Operational requirements include the following:

3.1.1 *Communication requirements (imposed by link establishment geometric/ kinematic conditions)*

*** Maximum communication range.**

Maximum communication range is different for the various UAV families and depends on the application (for instance typical values are around 100 nautical miles for tactical UAVs and more than 500 nautical miles for Endurance UAVs).

*** Distortion Phenomena**

The UAV Data Link suffers fading / multipath distortion phenomena due to atmospheric distortion, ground reflection and others factors (see choice of modulation with suitable distortion robustness).

*** Doppler Effect due to UAV / Ground Station relative motion**

The airborne terminal may move fast enough to generate a consistent Doppler frequency shift phenomena.

3.1.2 *Link Availability Issues*

*** Close–in and Long Range Availability**

The communication (link availability) has to guarantee a full coverage both during close–in operation (e.g. during landing) and at long range (e.g. for payload data transmission and navigation).

*** System Link Availability**

The link availability has to be guaranteed only during flight mission, as a rule not in extremely adverse weather conditions and anyway inside the UAV operating envelope. In any case adverse weather conditions along the complete communication path are unlikely to occur. Very high values of link availability, usually required for point–to–point fix radio link installations (over 99%), are typically not required for UAV.

As a rule of thumb, a typical availability value suitable for UAV applications is 90% (Crane Rain Model region H).

*** Line of Sight Availability**

To achieve low detectability (low RF power) and the required throughput (over some Mb/s) the propagation losses have to be reduced, this calls for UAV and Ground Station in mutual optical visibility.
To obtain OTH operation it is necessary to make use either of satellite Data Links (whose utilization may be troublesome when synchronous high data rate or high update rate are required) or of a Radio Relay System.

3.1.3 *Real Time Capability (Command&Control Update Rate)*

To allow real–time control of the mission and data analysis from the Ground Station, the Command&Control and the sensor Data Link has to be immediately available from the UAV to the Ground Station with reduced transmission latency (typically in the order of a hundred of milliseconds, or less during critical phases like landing).
A critical issue is the launch / recovery message update rate on down and up links too; typically a rate of 20–25 Hz is required even if some systems call for higher update rate (more than 50Hz).

3.1.4 *Multi–UAVs operation capability*

Multi–UAVs operation capability (especially for a military environment) involves two main issues:

* The capability to Control different UAVs from only one Ground Station (or the same Radio relay) using TDMA or FDMA broadcast techniques.
* The capability to operate in the same scenario with different UAVs, without reciprocal RF interference, using different identification codes and operative frequency bands.

3.1.5 *Multi–Users Capability*

Multi–Users capability can be considered under the following aspects:

* The capability to allow UAV payload Data exploitation to different users, (e.g., for a maritime/land environment, to broadcast the available information both to the control ship and to the landbased forces).
* The capability to allow hand–over from a Control Station to a different one.

To cope with these requirements, the UAV Data Links may make use either of multiple links (a point–to–point link plus a satellite one) or of a multiple beams / broadcast link.

3.1.6 *Low interceptability and Data Protection*

Several applications (military and non–military) require a low level of interceptability and a suitable grade of Data Protection; lack of Data Protection can ease operational intelligence, enabling a timely and efficient UAV interdiction (jamming, confusion, physical destruction) carried out by enemy forces. Suitable frequency band selection, directive antennas, ECCM / Data Protection Techniques are therefore required for several applications.

3.1.7 *Jamming robustness*

For military applications the UAVs are required to operate in a battlefield environment; Data Link is therefore expected to be operational in severe ECM scenarios. High immunity to enemy ECM is to be properly provided exploiting suitable frequency bands allocation and use of ECCM techniques (e.g. Frequency Hopping or Direct Sequence Spread Spectrum).

3.1.8 *UAV Targeting*

For military applications, (e.g. to allow precise target location preliminary to engagement or targeting), the UAV Data Link may be required to encompass means to define the UAV position without use of airborne sensors (e.g. GPS), preferably through the use of techniques and systems featuring high availability during battlefield operations.

3.1.9 *Interoperability*

*** Definition of interoperability**

In view of the growing number of multi–service applications of UAV systems, a strong requirement of standardization is envisaged. Various areas are identifiable where common elements have already been developed or are under development for different applications.

The ideal solution for interoperability would be a common UAV system. Accepting that this solution is unlikely to be feasible, the goal is to strive for as much commonality as possible between systems and achieve then interoperability.

Interoperability for UAV systems may be defined at three different levels:

Level 1 – Battle Force Interoperability;
Level 2 – System Interoperability;
Level 3 – Segment Interoperability.

These three levels of interoperability are defined as follows:

- **Level 1 Interoperability** (reception of payload data)
  Level 1 reflects the ability of a properly equipped platform, other than that controlling the UAV, to directly receive the UAV sensor down–link, process and display the sensor data.
- **Level 2 Interoperability** (Level 1 + UAV and UAV payload control)
  Level 2 reflects Level 1 interoperability plus the ability of any properly equipped platform to take and implement control of an UAV air vehicle and payload in the performance of a specific mission.
- **Level 3 Interoperability** (Level 2 + UAV take–off, landing and logistic support)
  Level 3 reflects Level 2 interoperability plus the ability of a properly equipped platform to:

  - launch and recover the UAV air vehicle;
  - refuel the air vehicle;
  - change out the UAV payload.

*** Interoperable UAV Data Links**

The methodology to achieve a given level of interoperability is the identification and control of the key UAV system interfaces. This may involve the specification of several characteristics which include the following families:

- standardized message and data forms;
- standard communications protocols;
- standard electrical and mechanical interfaces;
- standard Data Link parameters;
- standard ILS Tools / Methodologies.

The conditions to be fulfilled, required to support the above defined interoperability levels, vary. To support the Battle Force (Level 1) and System (Level 2) Interoperability, parameters must be defined at the message format / protocol and data link parameters levels. For Segment Interoperability (Level 3), the affected parameters must be defined at all the above five families of characteristics.
To reduce costs and increase interoperability, the system should have as many common components as possible and use or adopt existing civil and military standards. To the maximum extent practical, the system design has to incorporate STANAGs, MILSTDs and DEFSTANs.
A NIAG Group (NIAG SG53) has been established to define recommendations to achieve UAV Interoperability. NIAG Group activities are currently in progress.

3.2 Technical Requirements

3.2.1 *Data Requirements*

Requirements / issues relevant to UAV data include the following:

*** Data typology**

Data dealt by UAV Links can be grouped in two main families:

- **Sensors / Payload Data typology**

  From a communication point of view, sensor typology mainly affects the down–link data rate. Three categories of sensors may be defined on the base of different data rates:

  + **Sensors featuring low information rate**
    (e.g. lower than 200 Kbit/s), like Meteorological, NBC, ECM sensors;
  + **Sensors featuring medium information rate**
    (e.g. 200Kbit/s ÷ 10 Mbit/s), like processed SAR/ISAR, compressed VIDEO/TV, compressed Flir, uncompressed Mw Radar image, Elint/ESM sensors.
  + **Sensors featuring high information rate**
    (e.g. over 10 Mbit/s), like raw SAR/ISAR, High Definition Video/TV, High Definition Flir.

- **Command / Control and Status Data Typology**

  Command, Control and Status Data (to control the UAV navigation, take–off/landing and payload) generate a low rate data stream (usually <200Kbit/s). The up–link throughput is therefore much lower than the down–link one, allowing therefore either a greater communication margin (using different rate for up and down link) or a reduced transmission time (using the same up and down link rate).

  Very important parameters for the Command/Control Data are the allowed maximum latency and the minimum up–date rate.

*** Data Compression and Preprocessing**

Preprocessing and Data Compression are commonly used to reduce the data rate to be transmitted without affecting the data information content usually redundant in raw uncompressed / unprocessed sensor data.
The most suitable compression or processing techniques are dependent on the sensor typology and the UAV operating requirements. For instance tactical UAVs using EO/IR sensors at low altitude do not typically present high intraframe redundancy (low compression between frame) and a still imagine compression technique may be preferred, this may not be true for endurance / strategical UAVs operating at higher altitude, where intraframe redundancy is generally present.

Compression techniques commonly used are MPEG, JPEG, M–JPEG, and Adaptive Differential compression (ADPCM).

*** Data synchronism**

Sensor information often has to be transmitted synchronously. Special care has to be taken when transmitting at high repetition rate over integrated data network (e.g. satellite links) and not by dedicated Data Links (Point–to–Point Data Links).

*** Data criticality**

Data criticality depends on the typology of the transmitted data. Payload Data and Commands may be identified as mission critical. Navigation Data may be identified as safety critical, especially when remote navigation over civil area, take–off and landing are involved.
The criticality level may affect both the acceptable information level of quality (discussed in the next para) and the HW necessary redundancy (e.g. for a safety critical Data Link, the utilization of more than one Command&Control Link maybe necessary for physical redundancy).

*** Bit Error Rate (BER)**

– **Transmitted Data Level of Quality**

The required level of quality of the information transmitted (BER) depends on the typology of the data.
For the Command&Control Data it is necessary a high Level of Quality to avoid error or latency (due to retransmission) in the command data, specially when safety criticality has to be considered (for instance BER equal to 10^{-6} or better).
For the sensor data the goal is to deliver data to the ground terminal for further exploitations and analysis: typically a lower quality level than for Command&Control Data may be accepted (for instance BER equal or better than 10^{-3}).

– **Error Correction Techniques**

If the required level of quality is very stringent, Error Correction Techniques may be used.
Radio Data Link BER being constant, the use of error correction code allows to significantly improve System BER value (the application requirement to be fulfilled). The Radio Bit Error Rate is the bit error rate due to the communication channel only (depends on frequency, link budget, modulation performance etc.). The System Bit Error Rate is the error rate on the transmitted bits of information and depends also on others factors different from the communication channel characteristics.

*** Data Latency**

The latency is the delay in receiving the transmitted signal due to processing / transmitting through the Data Link.

Latency is very critical during some phases of the UAV Mission (for instance during take–off and landing) or when a particular data processing is required (for instance man–in the loop operations). In such cases a transmission latency of few hundreds of milliseconds or less may be required.

3.2.2 *Standards / Data Protocols*

In our knowledge there are not applicable / mandatory specific or de–facto standards for the UAV Data Links.
Standards STANAG 7085 and STANAG 7023 from the air reconnaissance community (applicability foreseen) are at present in the definition / ratification phases.
STANAG 7085 provides guidelines to be followed for the structure and the architecture of Analog Point–to–Point, Digital Point–to–Point and Digital Broadcast Data Links.
STANAG 7023 establishes standards for both the transport architecture / data format of reconnaissance imagery data and the type / data format for the auxiliary data (information necessary to process and exploit imagery data) to be transmitted between air reconnaissance systems and surface exploitation systems.

3.2.3 *Band allocation*

The selection of the Operational Frequency Band stems from a balanced trade–off among the following main issues:
* ECM and detectability considerations;
* Link budget analysis;
* Size and Power availability;
* Frequency Band allocation due to existing regulations.

The first three aspects will be analyzed as part of the design criteria in the following paragraphs concluding that use of high frequency band (above 10 GHz) is necessary.
Specifically, for UAV Point–to–Point Data Links and in general for Mobile Service (Point–to–Point and Broadcast Data Links), the current NATO Joint Civil / Military Frequency Agreement (NJFA) identifies the following bands:

* **14.62 – 15.23 GHz** NATO Harmonized Band type 1 for fixed – mobile services. Specified by NATO agreement for the radio guidance links and for transmitting real–time pictures from remotely piloted devices;

* **26.5 – 27.5 GHz** NATO Harmonized Band type 1 for fixed – mobile systems;

* **36 – 37 GHz** NATO Harmonized Band type 1 for fixed – mobile systems.

3.3 Constructive Requirements

3.3.1 *Size / Weight / Power*

Airborne environment sets the harshest limits for size, power and weight (SWP). Size, Weight and Power constraints affect the architectural choices of the equipment (for instance the utilization of a half–duplex time sharing approach optimizes SWP, even if it is more critical for latency and update rate), the frequency band (trade–off between reduced dimension and higher propagation losses), the equipment installation (allowable thermal dissipation), the airborne antennas typology and installation.
As result the SWP constraints on the airborne RF power and the antenna gain affect the link budget and the characteristics of the ground segment.
As a rule of thumb the airborne equipment shall be realized limiting its size, power and weight. Environmental constraints of the airborne platform (mechanical stress, temperature range) shall be carefully considered as well.

3.3.2 *Antenna dimensions / installation*

Antenna size and installation is a critical issue for the airborne terminal. The antenna typology depends on the available space (the UAV family considered, e.g. tactical or endurance) and the Data Link typology (e.g. point–to–point, satellite).
With high frequency links (due to link budget consideration and reduced equipment size), use of directive airborne antennas, placed on steerable and stabilized platforms, is generally advisable and often mandatory.

3.3.3 *Interfaces*

The HW interfaces, between the Data Link equipments and the Flight Management System or the Ground System Control Station, shall be chosen in accordance with two different requirements:

* use of available military / commercial standards for interoperability / interchangeability reasons and cost reduction considerations;
* capability to transmit the required throughput (up to some tens of Mbit/s).

Due to the lacking of Data Link Standards requiring the use of specific interfaces (STANAG 7085 is not yet finalized and only provides architectural guidelines), use of common standard interfaces for the airborne terminal, like Arinc429, 1553 or EFA bus for data and/or CCIR / RS 170 for Video, and for the ground terminal, like Ethernet, FDDI, ATM LAN for Video–Data and/or CCIR / RS 170 for Video, is advisable.

3.3.4 *Modularity / Flexibility / Up–grade capability*

The Data Link should be designed following a modular approach allowing modifications of key parameters like the external interfaces (due to the inclusion of different sensors), the RF transmitted power (to increase range) or the throughput rate, without a complete redesign and, as much as possible, only with FW redesign or with the inclusion of extra modules to a common Data Link kernel.

4. CONSIDERATIONS ON UAV DATA LINK ARCHITECTURE

For UAVs, the functions described in section 2 and the requirements described in section 3 are typically met with a Data Link configuration based on a primary wideband data link plus one/two additional redundant data links.
Additional / redundant Data Links may be either wideband Data Links to get specific functions extension (for instance UAV handover between two Ground Stations or OTH Link operation), or narrowband Data Links for redundancy/safety considerations (for instance Command&Control Data redundant transmission).

4.1 Primary wideband link

Primary Link function is to provide a wideband communication channel for payload information and Command&Control Data between the UAV and the Ground Station.

Basing on the requirements listed in the previous paragraphs, the main characteristics of the primary link can be summarized as here below:

* Capable to transmit / receive in real–time: sensor data / commands, command / control data during navigation and landing;
* Bi–directional (to allow simultaneous up–link and down–link operations);
* Point to point (due to low interceptability requirement and Link Budget considerations);
* High ECCM protection, Low interceptability, Data Protection.

4.2 Redundant wideband link

A redundant wideband Data Link may be used to perform additional functions like:

* Physical redundancy in all mission phases If required for mission/data criticality, a high link availability and a low BER may be necessary. A very high integrity for payload / mission data can be achieved only using an additional primary wideband link (whose characteristics are high communication margin, data coding / redundancy, spread spectrum technique);
* Capability to operate as relay in Over The Horizon (OTH) operations;
* Additional channel capacity (e.g. simultaneous use of various sensors);
* Simultaneous data transmission to various Ground Stations for multiusers simultaneous data exploitation. For instance a simultaneous point to point transmission at maximum range plus a broadcasting transmission at close range (e.g. during amphibious operations, close range transmission to terrestrial forces and long range transmission to maritime forces).

The same characteristics of the primary link are typically necessary with specific features to fulfill the particular functions required.

* For multiusers operations the redundant wideband link may be integrated with the primary link and the RF section designed to allow simultaneous utilization of various antennas (e.g. a directive antenna plus an omnidirectional one). For some applications redundant wideband link may be only a mono–directional link (down–link) to solely allow payload information exploitation;
* For data link relay applications, in the relay UAV typically the redundant primary data link will be functionally independent, but physically integrated with the primary data link (in order to achieve equipment configuration optimization and to control mutual interference).

4.3 Additional command / control narrowband link

Main function of an additional narrowband link is to guarantee Command&Control data redundancy during all the mission phases. Other typical functions can be retrieved among the following:

* High integrity data redundancy in specific mission phases (e.g. during navigation over civil areas or landing);
* Simultaneous control / monitoring of an additional UAV (or more UAV in TDMA) by the Ground Station;
* Simultaneous control / monitoring of the currently used UAV by two or more Ground Stations (e.g. during UAV control handover);
* UAV sensor data broadcasting to additional Ground Stations typically at reduced range or with reduced data "quality" (e.g. lower resolution and/or lower frame rate).

Typical characteristics of narrowband redundant Data Link are the following:

* Capability to transmit/receive command/control in navigation and in landing;
* Capability to transmit/receive sensor data/commands with reduced performance/ quality;
* Bi–directional;
* Broadcasting;
* ECCM / data protection.

4.4 Satellite Data Links

As for the Point–to–Point Data Links, Satellite Links may be divided into two main categories:

* Wideband Links (up to some Mb/s);
* Narrowband Links (up to some tens of Kb/s).

Satellite Links may be used for UAV operations with some limitations with respect to Point-to-Point Data Links due to:

* onerous installation in terms of SWP requirements (extremely high propagation losses and, therefore, need for high antenna gains and RF power);
* precise installation and accurate antenna pointing required (for wideband links);
* Criticality to achieve latency, real-time, up-date rate and synchronism requirements (due to complex relay operations, satellite links may not guarantee the high up-date-rate and low latency requirements, consequently real-time operations may not be performed).

Satellite Links may be used as redundant data links for near real-time operations.

A list of typical additional function is given below:

*** Wide Band Link**

- OTH Link Operation (UAV monitoring and/or payload data reception), without relay platform;
- UAV Data broadcasting to additional Ground Stations (with possible performance reduction, but at extended operational range);
- Additional channel capacity.

*** Narrow Band Link**

- Redundancy in specific mission phases (navigation).

4.5 Final Considerations

Accordingly to the above classification, the present paper will address design criteria and considerations for the primary link, even if these criteria can be easily extended to additional / redundant Data Links too.
Satellite Data Link system design presents however some additional issues which are not analyzed in the present paper (e.g.: satellite selection; satellite data channel requirements; link synchronism requirements; link up-date rate and latency requirements; UAV antenna dimensions and pointing accuracy; UAV antenna installation constraints).

5. DATA LINK DESIGN CRITERIA

Accordingly to the requirements previously listed (para 3), this section addresses the general design criteria to be followed in the development of a Primary Link for UAVs.
The Data Link design results from many complex trade-offs between different parameters. The design process is an iterating process, schematically it may be split in six different phases:

1. The Frequency Band Availability Analysis;
2. The Analysis of Application-Dependent Constraints (e.g. available standards or main system constraints);
3. The Link Budget Analysis;
4. The Analysis of the Data Protection Requirements and ECM, Jamming rejection, Low Interceptability constraints;
5. Analysis of application specific features.
6. The verification of the compliance with the Size, Weight, Power constraints and of the Communication and EMC requirements;

The results of the different analysis steps should be the following:

1. Definition of the possible operating frequency bands to be considered in the design process and evaluation of the operating compatibility with other systems/applications;
2. Definitions of key parameters which either are already derived by available standards or stem from system considerations (e.g. modulation type to cope with distortion phenomena, frequency stability to cope with Doppler effect);
3. Definition of possible sets of main link parameters (like gain, RF power and others), as function of frequency, modulation type, power (to guarantee the communication requirements, e.g. range and rate). Preliminary analysis of the equipment architecture;
4. Definition of the equipment architecture to satisfy ECM and jamming rejection considerations, for instance type and characteristics of the spread spectrum techniques (e.g. frequency hopping rate and bandwidth), evaluation of the different frequency bands against ECM constraints and requirements;
5. Analysis of the Data Link additional functions (for instance need of signal processing, need of Antenna Switching/steering devices)
6. Verification of the selected design parameters and architectural choices to meet the SWP constraints and the communication / EMC requirements.

5.1 Frequency Band Availability Analysis

As anticipated in section 3.2.3 three frequency bands are recommended for mobile data links:

* 14.62 – 15.23 GHz;
* 26.5 – 27.5 GHz;
* 36 – 37 GHz.

The use of the 26.5 – 27.5 GHz and 36 –37 GHz bands, due to the high propagation losses (free space plus losses due to rain, fading and others), requires high gain antennas and high RF power.
Such antennas are likely to require stabilized platforms to be correctly pointed; moreover the RF devices are less efficient in these bands than at lower frequencies.

The use of the 26.5 – 27.5 GHz and 36 – 37 GHz bands appears therefore not advantageous with respect to the 14.62 – 15.23 GHz one.
The possible use of frequency band different from than the 14.62 – 15.23 GHz one will be further technically discussed, even if it can be anticipated that the most suitable band for primary Data Link appears to be the J band.
The 14.62 – 15.23 GHz band is, moreover, the only one specified by NATO agreement for the radio guidance links and for transmitting real-time pictures from remotely piloted devices (UAV typical application).

5.2 Analysis of Application Dependent Constraints

The main requirements to be considered in the UAV Data Link design process are those based on system constraints arising from the inherent characteristics of the specific UAV system or from applicable standards.

5.2.1 *Interoperability constraints*

As anticipated in section 3.2.2 in our knowledge there are not mandatory / applicable standards for UAV Data Links.
A Data Link standard should define a set of key parameter to allow interoperability between various equipment (see para 3.1 Operational Requirements – Interoperability).
Key parameters and architectural choices like the following ought to be defined:

* The down / up links sharing approach (time–sharing or frequency–sharing);
* The frequency band;
* The Data Format / Protocol;
* The modulation type and baud rate;
* The ECCM Techniques;
* The Synchronization Techniques and others.

The standardization of these key parameters should fix most of the Data Link architectural and technical choices and would limit flexibility in equipment design.

5.2.2 *Effects of UAV motion*

The frequency shift generated by the Doppler Effect due to UAV motion is equal to fd = (vr*fo)/c where

fd = Frequency Doppler shift;
vr = target speed;
fo = RF signal frequency;
c = Speed of Light.

This frequency shift, especially when coherent demodulation is used, has to be considered in the determination of the demodulation and carrier recovery techniques and forces the utilization of an extremely precise frequency reference (with respect of the expected environment and the SWP constraints), both on the airborne and the ground terminal.

5.2.3 *UAV Targeting*

As previously indicated, the Ground Station may be required to determine, with a suitable degree of precision, the position of UAV targets. This operation requires the capability both to post–process the sensor information and to calculate the UAV position itself.
The latter operation can be achieved, for instance, either using UAV navigation system position data, transmitted through the data link, or determining the UAV distance and bearing with respect to the Ground Station with monopulse tracking techniques (bearing) and DME techniques (distance). With the second approach a highly accurate Absolute Reference System is then necessary to derive the bearing information from the monopulse tracking angle.
For the same application, the second approach, though involving a more complex Ground Station in terms of antenna and receiver, may be preferred due to its sure availability in any operative situation (UAV navigation data precision is often GPS availability dependent).

5.2.4 *Maximum data latency and up–date rate*

As previously stated latency and up–date rate are critical issues. Point–to–Point Data Links are preferred since they do not involve complex relay links like satellite links.

The latency arises as sum of various contributions and it is, for instance, due to:

* transmission delay;
* delay in processing information by the Data Processor or the Data Link (architectural choices);
* delay due to Error Correction Coding.

The transmission delay can not be reduced since it only depends on the link range.
Error Correction techniques deeply impact on the latency. Automatic Repeat Request codes are often not suitable since they involve a transmission repetition and add further communication and processing delay.
Convolutional encoding may be as well not suitable since they involve complex calculation over long bits blocks (complex for high data rate). Cyclic Codes (like Golay or Hammings), even if less powerful, may be preferred
Delay in processing may be affected by architectural choices. A half duplex system (Time Division approach, same frequency channel shared between up / down links) even if characterized by an higher latency due to its inherent philosophy, with proper implementation choices may be suitable as well like a full duplex system (Frequency Division approach, different frequency channels between up / down links).
Half duplex systems have disadvantages (e.g. required high rate of multiplexing between up / down links to satisfy the up–date rate/latency requirement) but present real advantages (e.g. the inherent lower complexity, the reduction of crosstalk phenomena and others more).

5.2.5 *Distortion Phenomena*

Due to the mobile nature of the air–ground communication, the link is affected by multipath and slowly fading phenomena. Using a suitable ratio between the carrier frequency and the modulation rate (typically less than 1/100), the fading and multipath (and therefore the signal amplitude variations) may be considered as frequency non–selective.
In case of amplitude modulation such distortion phenomena directly affect the information content (expressed as an amplitude variation over a RF Carrier).
In case of phase modulation, being the distortion phenomena typically non–selective with frequency, the information content, expressed as a phase/frequency modulation, is much less affected by distortion phenomena. Moreover phase modulations ease the use of AGC receivers to provide a constant level to the demodulator input.
Phase modulations are, as well, less affected by intentional amplitude distortions like enemy jamming.

5.2.6 *Recommendations*

The following design recommendations may be derived from this preliminary system analysis:

* Key parameters have to be defined according to the available standards;
* Digital phase modulation techniques, to cope with expected distortion, ought to be selected;
* Evaluations of the system frequency stability performance and analysis of the demodulation and carrier recovery ought to be carried on to determine techniques suitable to withstand the expected frequency shift;
* Utilization of Error Correction Code and of architectures suitable to meet latency and up–date rate requirements need to be evaluated.

5.3 Link Budget Analysis

After the analysis of the available standards and the definition of the system constraints, the system feasibility is evaluated through calculations of the Link Budget.

The link budget analysis includes evaluation of the path gain (e.g. transmitted power, Antenna gain) and losses (propagation

losses, implementation losses, communication margin), to define a suitable signal level at the demodulator receiver.
Main boundary constraints to the problem are the required LOS Data Link range, the necessary down-link throughput, the data quality at the receiver (BER) and the link availability.

5.3.1 *LOS Data Link Range and Link Availability*

The Data Link Losses may be separated in two main categories:

* The Propagation Losses due to spherical propagation of the RF signal;
* The losses due to rain, clouds or fading. These losses, or likewise the Communication Margin (the margin to be consider over the propagation losses), may be derived from the specified Link Availability.

The propagation losses are proportional to the square of the link range; longer range requires therefore higher gain in terms of greater transmitted RF power or larger antennas, which are extremely expensive in terms of size and power availability/dissipation.
The required link availability defines the link communication margin to be considered over optimum propagation conditions.
A higher link availability calls for a greater communication margin, therefore greater transmitted RF power or larger antennas.
Link availability being constant, the necessary communication margin increases with the use of higher operating frequency.
The communication margin especially increases with frequency when a high link availability is required. Considering a 100 nautical miles link and two possible frequency bands (the first around 5 GHz, the second around 15 GHz), the Communication Margin difference between the 5 GHz and the 15 GHz cases is about 10dB when a 90% link availability is required; the difference rises to over 100 dB when 99% link availability is required.
Being the typical link availability required for UAV Links around 90% (see para 3.1), the use of the 15 GHz Band is viable since the greater communication margin required may be compensated by the possibility to use smaller and more directive antennas on the ground and the airborne segments. For instance in the 15 GHZ case, where an antenna of 20 dB maximum gain for Tactical UAV may be used without requiring complex stabilized platform (10^{o} Az. / 40^{o} El. to cope with the UAV rolling and banking), the antenna presents a reduced size (approx. 10*6*30 cm) which eases its installation.

5.3.2 *Data Link Throughput*

The propagation losses are proportional to the link throughput. As for the range, larger rate requires higher gain and therefore greater transmitted RF power or larger antennas.
Due to the typical redundancy of the unprocessed raw sensor data, in the trade-off between Data Link throughput and RF Power / Larger Antennas, it is usually preferable to consider the utilization of data compression / processing techniques to reduce link Data Rate.

5.3.3 *Data Link Quality (BER)*

As anticipated in section 3.2.1, the Data Link Quality (System BER) depends on the Radio Link BER and other factors such as the Error Correction Techniques which allow the correction of wrongly demodulated bits of information.

*** Radio Link BER**

Pending the selected modulation type and the demodulation technique, the required Radio Link BER defines the minimum signal level to the demodulator receiver.
A more severe BER requirement increases the minimum signal level (sensitivity) necessary at the receiver input and involves a greater transmitted RF power or larger antennas.
The choice of the demodulation technique is therefore particularly important: a coherent demodulation technique, even if more complex to be implemented, requires a considerably lower signal level than noncoherent demodulation. Due to the cost (in terms of dimension, power availability and dissipation) of a greater RF Power or of larger antennas, a coherent demodulation approach should be therefore preferred.
Likewise, to allow a long communication range, the modulation type should be selected to increase modulation BER sensitivity with respect of band-width occupation.
Figure 1 shows, for various modulation and demodulation techniques, the required ratio Data-Rate/Channel-Bandwidth (Rb/Bw) and the Signal-to-Noise ratio (Eb/No) necessary to achieve a BER of 10^{-4}. Non-coherent demodulation techniques present a penalty of some dBs with respect to coherent techniques. MSK / OQPSK modulations techniques present an advantages of over 3 dB with respect to others phase/amplitude binary modulation techniques (FSK, DPSK or OOK).
Figure 2 shows, for the same modulation and demodulation techniques, the required ratio Data-Rate/Channel-Bandwidth (Rb/Bw) and the necessary Signal-to-Noise (S/N) ratio to achieve a BER of 10^{-4} when optimum demodulation filters are used (demodulation filter bandwidth equal to channel bandwidth). Optimum binary modulation techniques (MSK / OQPSK) present an advantages of several dB on M-ary modulation techniques (M-PSK or M-DPSK). The latter techniques allow a smaller bandwidth occupation (Rb/Bw) to transmit the same Data Rate.
Bearing in mind the above considerations, digital binary phase modulations like OQPSK or MSK and coherent demodulation techniques should be preferred for UAV Data Links.

*** Error Correction Codes**

If the required level of quality is very stringent, it may impose a minimum signal level at receiver difficult to be achieved with reasonable RF power and antenna gain. In this case the use Error Correction Techniques is suitable.
The Error Correction Techniques basically rely on three different methods:

- repetition of the incorrect transmitted word;
- addition of a redundancy to the data stream which allows bits errors correction (for instance Cyclic Code or Forward Error Correction Code);
- utilization of a binary convolution on the bit stream (interleaving code).

The first technique is not suggested (especially when high update rate are required) since it may increase the transmission latency more strongly than the others.

5.3.4 *Recommendations*

Accomplishment of the link budget analysis, in accordance with the requirements previously listed and bearing in mind the SWP constraints on the airborne terminal, makes possible to define a set of main link characteristics, like:

- Overall path gain;
- Airborne antenna gains and RF Power;
- Airborne implementation losses;
- Modulation/demodulation type;

- Utilization of Error Correction Techniques;
- Ground antenna gains and RF Power;
- Ground implementation losses.

The following design recommendations may be derived (These results are acceptable as well for Non–Military applications since do not encompass yet jamming robustness or low–detectability considerations):

* Use of binary phase digital modulations (to increase sensitivity with respect to bandwidth occupation);

* Use of coherent Demodulation techniques (to improve receiver sensitivity);

* Possible use of Correction Error Codes (to increase data level of quality);

* Minimizing the implementation losses with possible use of separate RF Front End to be connected directly to Antennas (to reduce cost in terms of size, power available/dissipated and Antenna gain);

* Modular approach.

5.4 Analysis of Data Protection Requirements and ECM / Jamming Rejection, Low Interceptability Constraints

5.4.1 *Data protection requirements*

As stated in the Technical Requirements (para 3.1 above), for military applications Data protection techniques may be required.
Due to security considerations and to follow a modular approach, it is preferable that the COMSEC device would be a stand–alone module which may be plugged–in or removed from the Data Link accordingly to the needs.

5.4.2 *ECM / Jamming Rejection, Low Detectability Constraints*

Military Data Links typically require the utilization of these features.
The first step to be met is the achievement of a low level of detectability / vulnerability to narrow band deceptive jammers by means of ECCM Techniques or with the utilization of high frequency and very directive antennas; the second step is to achieve a low level of detectability / vulnerability to broad band jammers, for instance by choosing a suitable spread spectrum bandwidth.
A number of techniques can be implemented in order to reduce the effect of jammers, which act as an extra sources of noise, among which a special attention is given to:

*** Spread spectrum techniques.**

Two main Spread Spectrum Techniques may be quoted:

- **Frequency Hopping Techniques**, where the signal frequency carrier continuously hops over the specified operating bandwidth with a fix hopping rate;

- **Direct Sequence Techniques**. These techniques operate a superimposition of a binary code to the binary data flow which spreads the information content over a larger bandwidth.

Each method has specific advantages / disadvantages, in particular:

- With direct sequence, at reception a deconvolution is necessary to extract the real information, this adds further latency and may be not compatible when reduced latency and high up–date rate are required. This extra latency is not present if frequency hopping techniques are used;

- With direct sequence the information content may be extracted only if the superimposed code is known. Likewise with frequency hopping the information content is detectable only if the enemy ECM are fast enough to detect the signal carrier frequency or if the pseudo–random frequency carrier generation code is known. Both the techniques decrease therefore the probability of interception (LPI);

- Direct sequence spreads information content over the operating bandwidth while frequency hopping concentrates it only on the currently used carrier frequency. Direct sequence is therefore more robust when only some few frequencies are jammed since part of the information content will be always transmitted. On the contrary, direct sequence may be less robust to distortion phenomena since the signal instantaneous bandwidth is much larger than the original one and the distortion phenomena can be considered as frequency selective;

- Direct sequence may present implementation problems when high spread spectrum bandwidth is necessary (over some hundreds of Mhz to achieve a suitable processing gain). The code superimposition process should in fact operate at hundreds of Mbit/s which is not always technically achievable or convenient to be implemented.

Due to the above considerations, when either low latency and high up–date rate are required or large spread spectrum bandwidth is necessary (some hundreds of MHz), frequency hopping techniques may be preferred.

The improvement over a single frequency band system (Processing Gain) is calculated as the ratio between the Spread Spectrum Bandwidth and the IF Receiver Bandwidth (consequently there is a trade–off between Gain and Data Rate). At lower frequency band, due to the lower propagation losses, the necessary gain and therefore the Spread Spectrum Bandwidth, suitable to achieve a suitable degree of vulnerability, increases.
The above considerations lead to the utilization of high frequency for the UAV Data Link.

The implementation of spread spectrum hopping techniques may increase the complexity of the Data Link since it requires the realization, for instance, of a synthesizer (usually the most complex part of the Data Link) capable of a fast selection of the desired frequency over a large hopping band and of a RF receiver and transmitter optimized over the required bandwidth and not at a single frequency.

*** Frequency Band Selection**

Regarding the choice of operating frequency band, the use of a high frequency band is preferred owing to the high propagation losses / technical difficulties to generate RF power for jammers and the larger spread spectrum bandwidth available for the transmitted signal.

*** Antennas Selection**

Use of highly directive antennas with reduced slipover is preferred. For detection purpose the use of such antennas is of vital importance on the ground segment where the most significant part of the system is present and the minimum detectability level has to be guaranteed.

*** Modulation Selection**

Use of modulations robust against amplitude distortion phenomena, like those usually generate by jammers, is called for (see choice of suitable modulations described at para 5.3 above).

5.4.3 *Recommendations*

Due to technical complexity and cost considerations, the Data Protection and ECCM Techniques are usually the edge between a military and non-military utilization. If their implementation is necessary, the following recommendations may be derived:

* Realization of modular Data Link which allows the plug-in / out of COMSEC devices if necessary;

* For cost reduction and possible interoperability between the military and non-military equipments, realization of modular Data Links which allow the inclusion / removal of ECCM devices without a complete system redesign, but, for instance, using different frequency synthesizers;

* Utilization, when required by ECCM – Data Protection considerations, of Spread Spectrum Techniques based on frequency hopping when either large spread spectrum bandwidth or low latency / high up-date rate are necessary;

* Utilization of high frequency band for ECCM considerations. The bandwidth 14.62–15.23 GHZ selected in previous section 5.1 is suitable also from an ECCM point of view.

5.5 Analysis of Application Specific Features

In addiction to the specific Data Link functions (to provide a communication link between the UAV and one or more Ground Stations), some additional features may be considered.

These additional functions are strictly relevant to Data Links, since they arise as system constraints imposed by the Data Link itself to perform the required communication function, or may be developed much more easily in integration with the Data Link equipment.

As additional functions the following may be considered:

5.5.1 *Antennas switching / steering / stabilization*

* To achieve multi-users communication more than one antenna is necessary. A switching unit, controlled using the relative position of the UAV with respect to the ground terminal, is necessary.

* On the UAV a steering platform is necessary to point the directive antennas utilized for long range communication. For point-to-point endurance UAV or satellite link, due to the high directivity of the required antennas, these platforms often allow the antenna stabilization as well; the size and weight of the ensemble of antenna plus the stabilized platform may be critical from an installation point of view.

* On the ground segment, due to the UAV targeting requirements, an exact relationship must be determined between the radioelectrical beam of the antenna and the geographical coordinates of the antenna itself. An accurate absolute reference System ought to be derived mechanically or electrically.

5.5.2 *Link management*

To allow the utilization of multiple links configuration (primary plus one or more redundant links), a link management unit is necessary to perform a coordinate management of the various links.

5.5.3 *Data multiplexing*

Simultaneous sensors data transmission from UAV is often required to perform data correlation and data fusion in the ground stations (e.g. Navigation plus EO/IR data for targeting). Sensor data multiplexing on the UAV and demultiplexing in the Ground Station is therefore necessary.

5.5.4 *Sensor signal processing*

Data compression / decompression, data protection coding, other image processing (like automatic video target tracking) may be required to be integrated within the Data Link.

5.6 Verification of Size Weight Power Constraints

The Size, Weight and Power constraints both force architectural choices and impose the use of special technologies to meet the tight performance required for the airborne terminal.

5.6.1 *Architectural Choices*

Among the architectural choices can be listed the following:

*** Selection of high Frequency**

The use of high frequency, even if more complex from a implementation point of view, allows the realization of equipments of smaller size.

*** Selection of Time Sharing Approach**

As stated in the operational requirements, for the majority of applications, the Data Link needs the presence of the down and up links with precise latency and up-date rate constraints.

As previously expressed, this may be realized using two different approaches:

- a full duplex system with two links (up and down) at two different frequencies (frequency sharing approach);
- an half-duplex system timed shared between up and down links (time sharing approach).

The first approach minimizes the transmission latency, maximizes the effective transmission baud rate and allows, if required, the utilization of the same baud rate for the up and down links. As major limitation the full duplex systems increase the equipment dimension, supply requirement, complexity and cost.
The second approach simplifies the SWP requirements and the system complexity (for instance the crosstalk and receiver possible saturation problems); as main disadvantages it gives origin to an extra latency (due to the time shared nature of the link) and reduces the effective baud rate.
The latency can be reduced by use of a multiplexing rate between up and down link whose minimum value is given by the required Control&Commands up-date rate.
The effective baud rate reduction may be minimum if the up and down links data rate are significantly different (e.g. up rate much smaller than down rate, as in the UAV Data Link where transmission of data from high information rate sensor is required); in this case only a reduce slot time may be dedicated to the transmission on the up-link (lower rate link).
The drawbacks listed above, with a sensible design, may be greatly reduced; the time sharing approach is then often chosen in presence of tight Size, Weight and Power constraints.

5.6.2 *Specific Technologies*

*** High Scale Integration Devices**

The use of such devices allows to reduce size and power requirements of IF, Demodulator/Modulator, Processing Sections, increasing the reliability level as well.

*** Solid State Amplifier and MMIC**

The use of Microwave Miniaturized Integrated Circuit (MMIC) and Solid State Amplifier allow to reduce the size and to increase the reliability level of the RF Front End.

5.6.3 *Recommendations*

Among the possible recommendations, the list reported here below deserves a special attention:

* Selection of high operative frequency to reduce equipment size;
* Selection of time–sharing approach when the SWP constraints are highly critical;
* Selection of specific technologies (high scale integration devices, Solid State Amplifier, MMIC) to minimize SWP requirements and increase system reliability.

As final recommendations it should be noted that the system design of a Data Link is an iterating process; the designer may need to repeat more than one time the design process, selecting different initial assumptions in order to optimize the Data Link characteristics.

6. DESIGN APPLICATION: INTEGRATED MULTIPURPOSE DATA LINK DESCRIPTION

As practical application of the data link system design and implementation, the Integrated Multipurpose J Band Data Link developed and realized in Marconi SpA is presented and the results achieved discussed.

6.1 Data Link Functions and Requirements

The Marconi Data Link is currently utilized both on tactical UAVs and helicopters (integrated by METEOR C.A.E and Alenia Difesa Radar Division) provided with a large families of sensors (e.g. ESM, EO/IR, MTI radar, LineScanner sensor, ..).

6.1.1 *Main Functions*

Accordingly to the data link role depicted in section 2, the primary function of the Marconi Data Link is to transmit, in real–time, the payload data plus the UAV C2 data, allowing the UAV Command and Control.

As additional functions the Marconi Data Link encompasses:

* A compression device based on a adaptive differential compression algorithm;
* A Ground Station Antenna Tracking system for precise targeting of the UAV;
* An Automatic Video Tracking (to be used with EO/IR sensors) for video targets tracking and targeting.

6.1.2 *Main Requirements / Characteristics*

According to the requirements listed in para 3, the Marconi Data Link is compliant with the following:

* The Marconi Data Link range is within the tactical UAV range with a down–link data rate of some Mbit/s and an up–link data rate of some tens of Kbit/s sufficient to allow the UAV command and Control. For the EO/IR sensors either a compressed full frame rate signal or an uncompressed full resolution slow frame rate signal (1 frame per second) may be transmitted;
* Different Data Level of Quality are required for the Command&Control Data and for the Sensor Data. The required values, analogous to those indicated in para 3.2 (Technical Requirements), are achieved also with the utilization of Error Correction Techniques on the Command&Control Data;
* The Marconi Data Link is required to support man–in the loop operations and to perform remotely controlled video tracking functions; the maximum latency is therefore a critical issue and special care has been taken to bound its value to some tens of milliseconds;
* As regards to long–range and close–in operation capability, the Ground Station is required to simultaneously operate with a high gain antenna (for long range communication) and a low gain antenna (for close–in operation). To guarantee mutual optical visibility between the UAV and the Ground Station up to three airborne antennas may be selected by the Air Data Terminal;
* Due to ECCM considerations and to meet the NATO Joint Civil/Military Frequency Agreement, the Marconi Data Link operates over the band 14.62 – 15.23 GHz Band;
* As regards to the ECCM capabilities, owing to the hopping ability over the 14.62 – 15.23 GHz band, the medium/fast hopping rate and the use of highly directive antennas, the Data Link shows a suitable protection level against Narrow Band Jammers; the large Spread Spectrum bandwidth and the choice of the proper frequency band give the Data Link a considerable level of protection against Broad Band Jammers.

6.2 Data Link Design

With reference to the recommendations derived by the Data Link Design Criteria (see para 5), the Marconi Data Link is characterized by the following system choices:

* Utilization of a binary phase modulation (MSK) to guarantee the optimum trade–off between sensitivity and bandwidth with a sufficient robustness to fade and multipath;
* Utilization of digital demodulation coherent techniques to improve sensitivity (coherent demodulation) and system reliability (digital implementation);
* Utilization of Error Correction Codes for the Command&Control data to improve the delivered data level of quality;
* Utilization of a half–duplex Time Sharing approach to meet the tight Size, Weight and Power requirements. Due to a sound design the time sharing approach meets the maximum latency and up–date rate requirements;
* Inclusion of the Antenna Switching Unit and of the Video Signal Processor (Automatic Follower device) within the Air Data Terminal to increase the equipment integration reducing dimension and production cost;
* Adoption of special provision to improve the EMC performance and assure the NEMP survivability. For instance: use of differential balance interfaces (reduce the harmfulness of common mode noise); use of double–braided cables and metallic external conduits (improve screen from external EMC radiation); availability

of a very low resistance path from the mobile to the fix part of the ground antenna; suitable thickness of the mechanics to assure protection against skin effect.

6.3 Air Data Terminal Implementation

The Air Data Terminal, depicted in picture A, is characterized by the following key features:

* Detached RF section (to minimize implementation losses) with High Power solid state HPA;
* Possibility to switch between different Down-Link Baud Rates to increase range or communication margin;
* Highly integrated and compact synthesizer with Spread Spectrum Hopping capability;
* Integrated RF Front End developed using a MMIC;
* RF, Power Supply and Processing sections realized with a modular approach to ease modification and maintenance;
* Video Compression Unit to allow continuous video transmission with down-link rate up to some Mbit/s;
* Use of standard interface for Command and Sensor Data like, Arinc429, 1553 or CCIR for Video;
* Medium Gain steerable, not stabilized antennas.

6.4 Ground Data Terminal Implementation

The Ground Data Terminal, schematized as in Figure 3, is divided in four units: the Antenna Tracking System (ATS), the Radio Frequency Unit (RFU), the Processing Unit (PU), and the RF Beacon (being used for alignment purpose during on-field deployment).

Pictures B, C, D depict respectively the Radio Frequency Unit, the Processing Unit and the Beacon.

Pictures E, F, G depict the Antenna Tracking System, the latter picture shows as well the Marconi rotary platform part of the test equipment used to simulate UAV trajectory during the preliminary system evaluation test.

The Ground Data Terminal is characterized by the following key features:

* High gain antenna for low detectability and long range communication;
* Low gain antenna (optional not shown in the picture) for close-in operation;
* Same RF transmitter/receiver channels, synthesizer and modulation / demodulation techniques used in the Airborne Terminal for maintainability and performance uniformity;
* Monopulse Tracking Ground Antenna and Integrated Distance Measuring Equipment (DME) for the precise determination of the UAV position with bearing and distance (RHO/THETA technique). The Airborne Terminal RF transmission is used as tracking signal source;
  The Ground Terminal makes use of monopulse tracking calibration techniques to compensate the GDT receiver channels phase and amplitude unbalance at the switch-on and during operations. These techniques ease the design and realization of the monopulse receiver channels whose phase and amplitude ought to be balanced to guarantee correct tracking operations;
* Internal Stabilization system for accurate leveling of the GDT.

6.5 Experimental Results

To validate the system design and the Data Link correct implementation, extensive tests have been carried out during the prototypic and production phases both in Marconi (with a suitable Test Site) and on field (with the final system configuration). The tests performed encompass the air – ground transmission of medium and low information rate sensors data (e.g. MTI Radar, EO/IR, ESM).

6.5.1 *Factory Tests*

The aim of the tests performed in Marconi was to finalize the Data Link development and to verify the required performance against a controlled test environment.
Marconi Test Site made use of a rotary turntable allowing to perform both Link RF and tracking tests simulating the real UAV dynamics with respect to the Ground Station.

The results achieved in terms of real link (BER, range), tracking / servomechanical and environmental performance, were in agreement with the expected design performance.

6.5.2 *Field System Tests*

The aim of the field tests, currently still in progress, is to prove the correct functionality of the complete system in a 'alike operating scenario' verifying, as well, the Data Link adequacy against fading and multipath.

The test already performed has shown the Data Link capability to fulfill all the functions and requirements specified.
The Data Link tracking of an air vehicle and transmission of the C2 / sensors data within the required range, even with extremely adverse weather conditions, were verified.
The achieved results confirmed therefore the suitability of the design choices (e.g. frequency band, modulation/demodulation technique, etc.) to provide the required communication function with an adequate quality level and within the SWP constraints.

6.6 Additional Function and Future Development

Marconi Data Link system design have been carried out emphasizing the modularity and interchangeability aspects; this choice is currently allowing the necessary growing capability to meet additional requirements not originally specified by Italian MoD.
Main additional functions, whose development is either being carried out or forecast for the Marconi Data Link, are:

*** Additional Operational Range**

A small detached HPA/LNA module is under study/development to be directly connected to the transmitting antenna. Such solution will minimize the installation losses leading to an increased operational range.

*** Multi Link Capability**

Specific Link Management Units are under study/development to allow the installation/utilization within the UAVs and the Ground Stations of a Multi-Links configuration system (e.g. a primary point-to-point Data Link plus a redundant Satellite link or others).

*** Additional Payload**

Marconi Data Link is currently capable to carry medium / low information rate data stream. The need to support high information rate data sensors (Wideband / High Resolution SAR, Multi / Hyperspectral Imagery Sensors) is foreseen for the next future.
To cope with this requirement, suitable implementation choices

are under investigation for binary phase modulation (MSK, OQPSK) modem up to and over 10 Mb/s.
Due to the modular approach followed and the digital modem implementation, only a partial redesign is foreseen.

*** Different Additional Interfaces**

Implementation of different external interfaces modules (e.g. LAN Ethernet or ATM) to allow direct connection with the Command&Control Stations is currently under study / evaluation.

*** Non–Military Applications**

As previously stated, the edge between military and non–military application is marked by the implementation of specific function (like UAV Tracking) or ECCM techniques.

The Marconi Data Link, due to its modular approach, allows the utilization either of simpler non spread–spectrum synthesizers or of non–tracking ground antennas operating, for instance, with the UAV navigation information provided by GPS and transmitted via the radio links. Even with such modifications, the other system performance (operating range, data rate, etc.) would be retained unchanged.

7. ACKNOWLEDGEMENT

The authors wish to acknowledge the Italian Ministry of Defence, Alenia Difesa, Radar Division and Meteor C.A.E..

8. REFERENCES

[1] Carlson A.B.
"Communications Systems"
McGraw Hill

[2] CEPT (European Conference of Postal and Telecommunications Administrations)
"CEPT Report concerning the Frequency Band 960 MHz to 105 GHz and Associated European Table of Frequency Allocations and Utilisations"

[3] NATO – Allied Radio Frequency Agency
"NATO Joint Civil/Military Frequency Agreement"

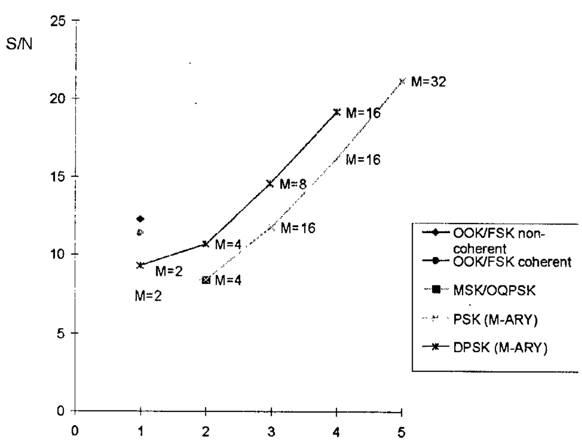
[4] NATO – Military Agency for Standardization
"STANAG 7023 AR – Air Reconnaissance Imagery Data Architecture"

[5] NATO – Military Agency for Standardization
"STANAG 7085 AR – Interoperable Data Links for Imaging Systems"

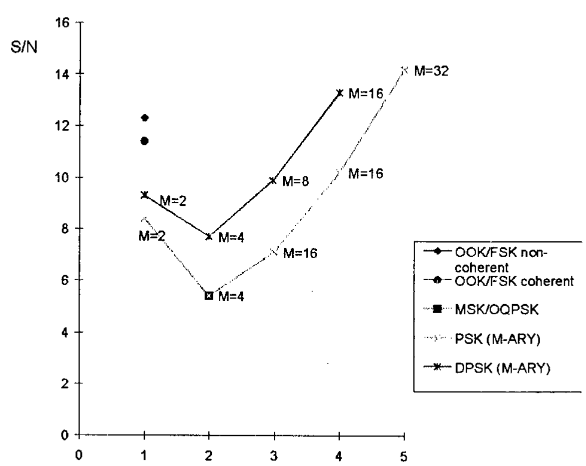
[6] Proakis J.G.
"Digital Communications"
McGraw Hill

[7] Smith D.R.
"Digital Transmission Systems"
Van Nostrand Reinhold Company

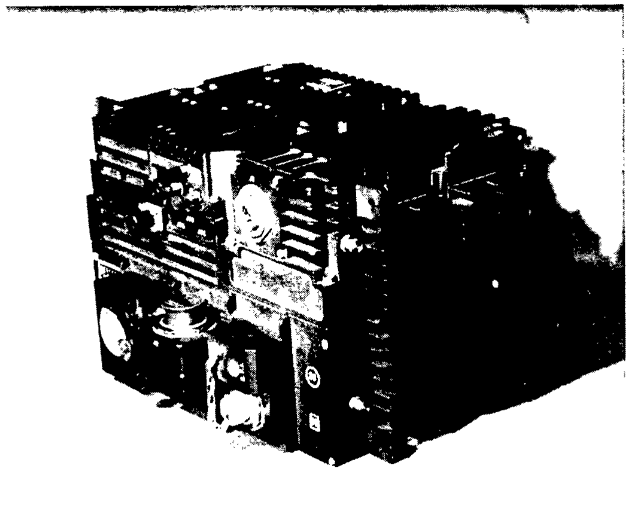
9. FIGURES



Baud Rate/Bandwidth Ratio Rb/Bw - Figure 1

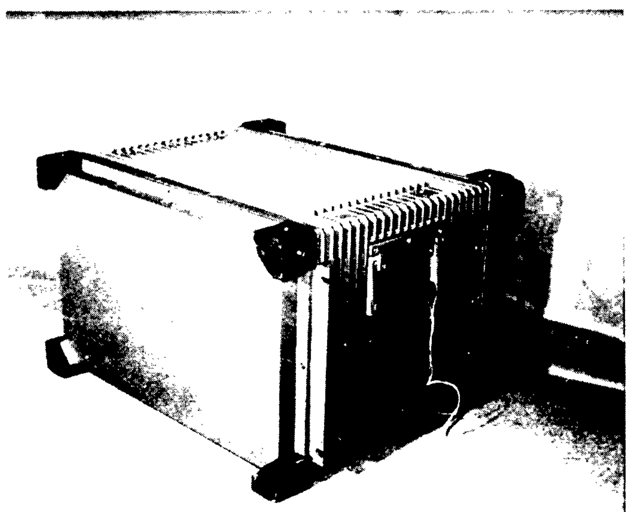


Baud Rate/Bandwidth Ratio Rb/Bw - Figure 2

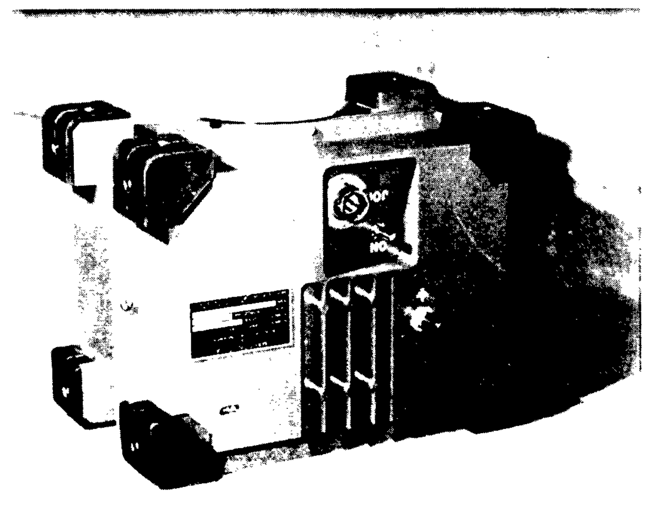


Picture A

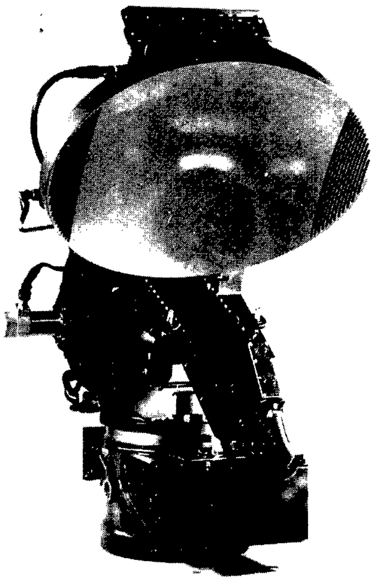
Picture B



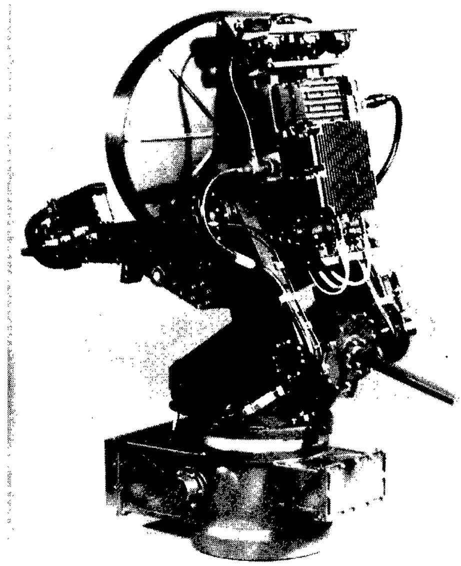
Picture C



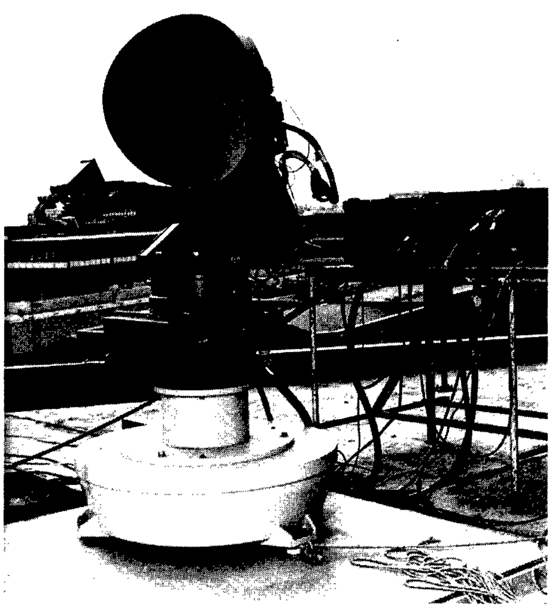
Picture D



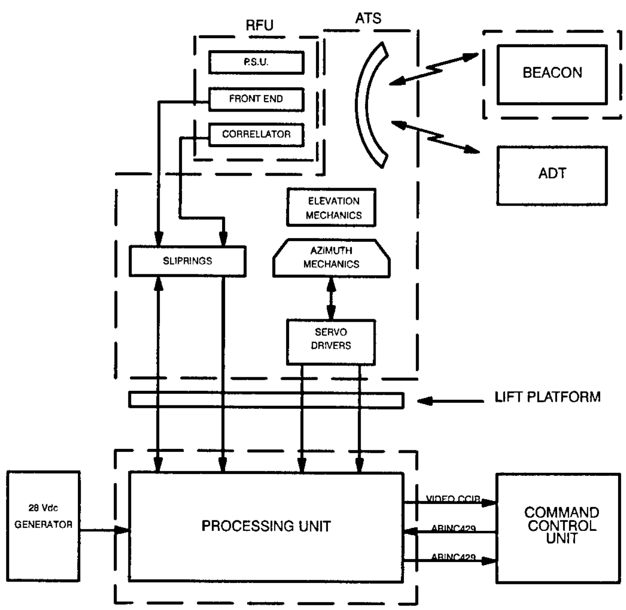
Picture E



Picture F



Picture G



GROUND DATA TERMINAL BLOCK DIAGRAM

Figure 3

Investigation of Human Performance Monitoring an IR-Camera View from an Unmanned Tactical Aircraft

Klaus-Peter Gärtner
Walther Krüger
Research Institute for Electronics and Mathematics (FFM) of the FGAN e.V.
Neuenahrer Str. 20, D-53343 Wachtberg, Germany
Tel: +49-228-9435 481
e-mail:gae@fgan.de

1. SUMMARY

Man-machine system performance on target designation and tracking tasks can be influenced by the design of the manual control subsystem including characteristics of the control device.

An experimental set-up simulates the control station of a human operator monitoring a computer display which shows the stabilized TV-camera view out of an unmanned aerial vehicle flying at low altitude. Using a hand-grip controlstick the operator can control the direction of the missile's camera to facilitate the designation of a target. After "lock on", further tracking of the target is made by an automatic tracking system. The operator has to monitor the tracker function and to make corrections if necessary.

Target designation by the operator becomes a critical task because the camera system has a narrow field of view to enhance good recognition. Thus target images move towards display edges in a short time. So the target designation task has to be fast and reliable.

To achieve near optimum operator performance three different types of control sticks are used and compared in an experiment: (1) a moveable stick (displacement), (2) a stiff stick (hybrid force), and (3) an unmoveable stick (pure force). Additionally the sensivity, i.e. the gain of the control signal, is being varied including a non-linear relationship.

Results of a test series conducted comparing linear and non-linear control gain showed no signifikant differences on performing the target acquisition task.

2. INTRODUCTION

In support of the man-machine interface design of a future unmanned aerial vehicle system, the remote operator's control activity was investigated. The operators task is to select a target in a given reconnaissance area and to make the proper target designation in time to bring the aerial vehicle onto the target during the end phase of its flight. To achieve near optimum operator performance, control stick type and control gain will be investigated.

Navigation of the aerial vehicle is conducted by a control station on the ground. As a requirement for target recognition the sensor picture of a infrared-camera is transferred to the ground station. The stabilized camera view is presented to the operator on a computer monitor. During an pre-programmed and automatically controlled cruising phase up to 60 km the operator can also follow the vehicle path via a map presentation on a second monitor. After the aerial vehicle reaches the target area the monitor and search phase begins.

Here the operator's primary activity takes place. First of all he has to detect relevant targets and then to identify or classify them. He then selects the target by bringing together target location and aiming cursor with his control device. This manual target designation initiates the end phase of the flight, which results in the automatic tracking system leading the aerial vehicle to the target. During the end phase as well the control device of the operator is activated, thus correcting of the aiming point is possible nearly until impact.

3. GEOMETRIC RELATIONSHIPS AND THEIR EFFECTS

The presentation on the monitor depends on the flying altitude and camera angles used. Figure 1 shows an example geometric relationship of a view from the aerial vehicle. The flying altitude is essentially determined by technical and tactical aspects. Determining factors are e. g. the limitation of surveillance at altitudes that are too low, the operational distance, and the speed of the aerial vehicle. An altitude of 150 m is assumed to be a favourable value.

The selection of flight speed is affected primarily by the operator's reaction time to events while watching the monitor. If speed is reduced, target designation is made easier for the operator. An assumed value for flight speed is 120 m/s.

Used in the monitoring phase is a fixed camera pitch angle resulting from the application of a rate gyro-stabilized camera line of sight until the target designation procedure is initiated.

Optimum starting camera settings were analytically determined by theoretical considerations. These settings turned out to be 4° to 7° pitch angle and 7° to 11° *vertikal view angle.* Derived from this by using a monitor height with a ratio of 3:4, was the *horizontal view angle* of 10° to 15°.

Paper presented at the AGARD MSP Symposium on "System Design Considerations for Unmanned Tactical Aircraft (UTA)", held in Athens, Greece, 7-9 October 1997, and published in CP-594.

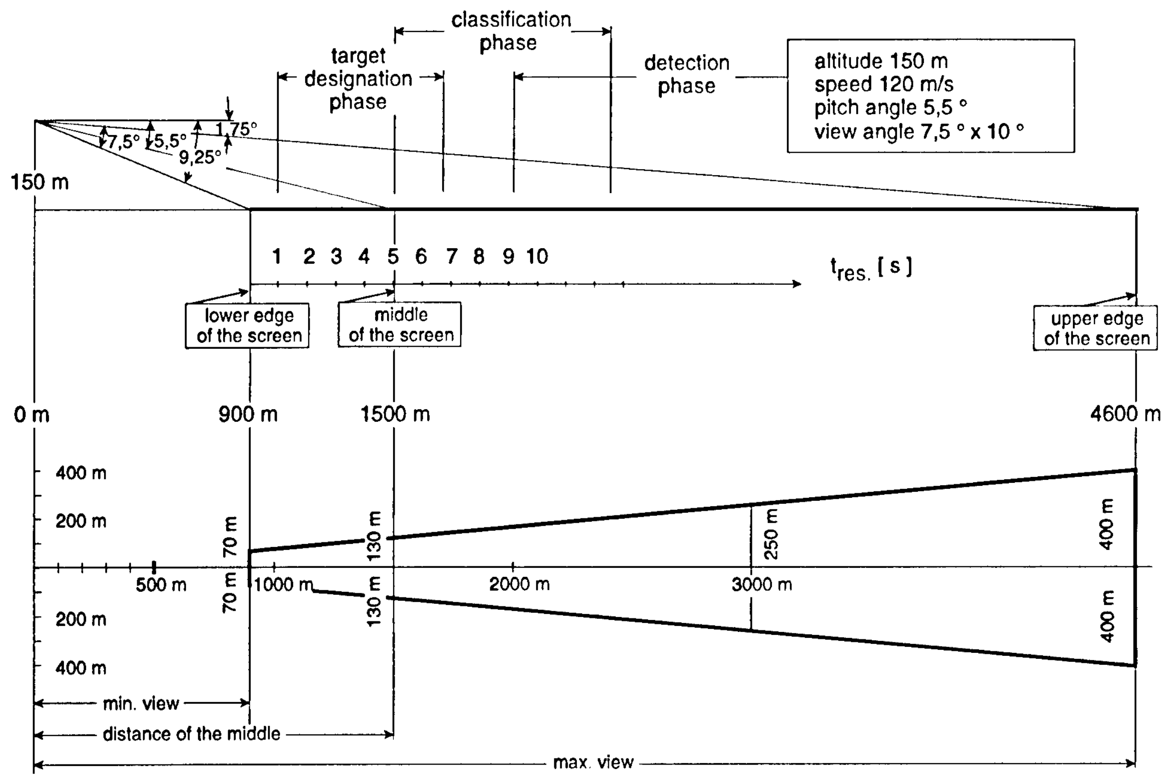


Figure 1: Geometric relationships

With the data used in Figure 1 there is a minimal viewing distance of 900 m, a maximal viewing distance of 4600 m, a front view width of 140 m and a back view width of 800 m. For the observer of the monitor the front view represents the lower edge of the screen and the back view represents the upper edge of the screen. (12% below the upper edge of the screen corresponding to a distance of 3000 m there is a 550 m wide field of view anyhow, which should be sufficient for monitoring within the target area). The center of the monitor results from the camera pitch angle and corresponds to the center distance of 1500 m. Furthermore, a time scale is given in the figure which indicates the time t_{res} remaining for an object in the target area until it disappears at the lower edge of the screen, insofar as camera direction (line of sight) will not be changed.

From these geometric and temporal values the operator's working areas for detection, classification, and target designation tasks can be estimated. Detection is defined as the state when "an object is found". The detection phase takes place in the upper quarter of the monitor and extends from the more distant areas down to 2000 m, corresponding to about 9 s of the remaining time. Identification and/or classification can take place anytime after detection but should take place before the time remaining is 5 s. This phase will vary in duration and may therefore overlap both the preceding detection phase and the following target designation phase. The decision making of target selection is essentially involved during the classification phase. A smooth transition to the target designation phase occurs next for which only 3 s to 5 s of the time remaining are available until the object disappears at the lower edge of the screen. Therefore, the target designation procedure has to be finished in time by locking on to the target, activating the tracker and handing over to the automatic final guidance (release for target attack, possibly with final corrections).

Because *camera parameters* have a determining influence on the operator's field of vision, the following considerations were important.

In order to reach a sufficiently high resolution or the field of view (which will be generated from 640 x 480 pixel sensor data) while considering the operator's time budget for target selection and designation, only relatively low camera view angles are possible, which corresponds to a telephoto lens. The camera pitch angle (angle under which the center of the picture can be seen) can be derived from the distant areas (below the horizon) which still should be visible at the upper edge of the operator's screen. The attempt to get high resolution by extremely low view angles is limited by ongoing reductions of the viewing field (especially the width of the visible area).

These considerations show that vertical view angles between 6° and 14° are promising. Concerning the camera pitch angle it can be noted that the upper edge of the field of vision should be 2.5° to 2° below the horizon so that distances up to 3400 or 4300 m are displayed; because beyond that the detection of details are hardly possible.

It should also be considered that close to the edge of the front view (at lower edge of screen) blur-effects can occur, which arise from the characteristics of the infrared-sensor (up to 20 ms integration time, if very high resolution of temperature differences is desired). Such blur-effects appear at distances of 600 to 1100 m depending on the view angle of the camera. (At 800 m in the actual example there is a blur zone of + -1 pixel using a 480 line picture, which would mean 1 mm on a monitor with a 24 cm height.)

4. OPERATOR'S TASK

To ensure good operability the system is improved in the sense that after the operator firstly is able to manually control the direction of the camera, he can than later use the advantages of the automatic target-following camera. Thus, after target designation a preliminary target can be kept in the center of the display by means of an image processing system that includes an automatic tracker.

The operational procedure for the operator is shown in the flow chart of figure 2:

During the search phase the monitor displays a fixed angle of view. If the operator detects a possible target or target area, he manually directs the camera towards the area of the desired target (or aiming point). By so doing the selected target comes to the center of the display, which is marked by a crosshair. After the "lock-on" button is pressed camera control is given to the tracker

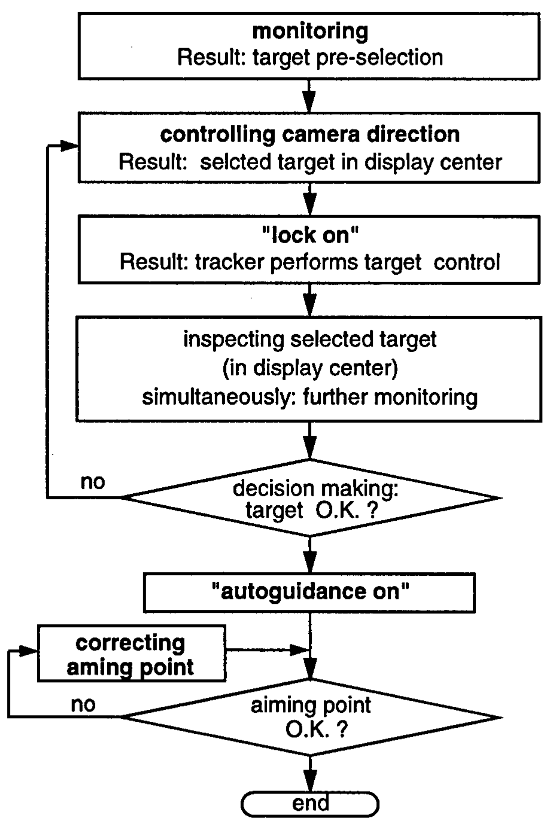


Figure 2: Flow chart of the operation procedure

which follows the target available (or the structure being there) at that time in the center of the display. Such the camera remains in direction to the given aiming point. The operator is able to move that aiming point with his control device within the close surroundings before the final target attack release while the "autoguidance" function is on.

Should the tracked object be classified by the operator as a non-target, the tracker can be disabled for the moment and be reactivated after a new positioning of the camera. The final target designation signifies the start of the autoguidance phase of the final target attack. The autoguidance phase can be started either by an additional button pressing or it can begin automatically because "lock-on" is not cancelled and a critical value of the camera pitch angle is exceeded (e.g. 12° corresponding to about 700 m distance to the target in the center of the display).

With regard to camera parameters to be selected it can be noticed that relatively small view angles are useful due to the system improvement using the target following camera. Starting point values for the view angle should be 7.5° vertically and 10° horizontally respectively. The fixed pitch angle of the camera for the detection phase (before "lock-on") should be chosen in a way that distances at which detections are probable are close to the center of the display. That is the case at 4°to 5.5° which is corresponding to distances between 2000 m and 1500 m.

5. PARAMETERS OF THE EXPERIMENT

The effects of several influencing factors have to be examined under experimental conditions in order to optimize the operator's performance. For the experiment the operator's control system will be simulated by means of a computer-generated display. This enables various values to be set for each parameter of interest for different testing conditions and offers a means for determining an optimal pre-selection of parameter values.

Camera parameters

The importance and significance of camera parameters have already been extensively discussed.

Flight parameters

The most important flight parameters are *speed* and *flight altitude*. They are mainly determined by the technical and tactical conditions. It is not necessary to vary flight altitude for the experiments, because it is possible to convert the camera parameters optimized for a specific altitude (essentially by means of the pitch angle) to a new flight altitude so that nearly identical perspective for the observer of the screen is achieved. For similar reasons flight speed does not need to be varied. By increasing flight speed the camera view has to be aimed more distantly (by means of a smaller view angle) in order to provide sufficient time for the operator to perform his task.

Control device

In manual control type and characteristics of control devices used can influence the operator's control perfor-

mance (e.g. [1]). If a control stick (as best choice for this rugged application) is used, it should be spring centered [2]. The question remains how much stick displacement to offer, if any [3]. Also, to be determined is the control gain and whether it should be constant across the entire displacement range. Gain characteristic be can also be made progressive which has the advantages of high control gain without their disadvantages [4].

Cursor control

Instead of the direct camera control by a control stick the operator can use an indirect steering mode which derives a command for the control of the camera from the changed position of the cursor on the screen.

6. SIMULATION SET-UP AND EXPERIMENTAL PROCEDURE

Simulated test conditions were set-up in order to experimentally examine the operator's performance in the target designation process as influenced by certain selected parameters (independent variables). The visual presentation for the experiment is a computer simulation. The simulated view from the aerial vehicle's camera while flying over a level landscape with different targets is shown according to the camera's view and pitch angles.

Stored in the computer is a simulated level landscape of 7.5 x 2.0 km that represents the target area. In this landscape targets can be inserted (views of tanks from different directions). An impression of the operator's view is given in figure 3. Flight time over the landscape would be about 30 s at a speed of 120 m/s, after which the simulated landscape would be exhausted. However 30 s is sufficient time to simulate the operator's activities of detection, classification, and target designation and to investigate the control activity depending on given experimental conditions.

In order to meet the real time requirements of the experiment and the limitations of computer processing time, the simulation of the landscape is limited to simple fields and roads. An attempt was made to give a temperature dependent appearance on the display as typical of infrared sensor data.

It was neither possible or desirable to simulate with full realism the visual conditions for the detection and classification phases with the available computer system (silicon graphics crimson VGXT). But visual realism requirements of the operational activities in the target designation phase which were the focus of the experiment, were met. Full visual realism in the simulation of the preceding identification and classification phases were not desirable because this would have meant a highly complex and variable sensor system return where targets appear less distinct and less distinguishable from background details. This would have required better trained subjects in the experiment to assure that target identification and classification during the experiment occurred early enough to leave sufficient time for the target designation task. By use of less realism, target identification and classification is made easier for less trained subjects while still assuring that sufficient time is left for the task of interest, namely the target designation task.

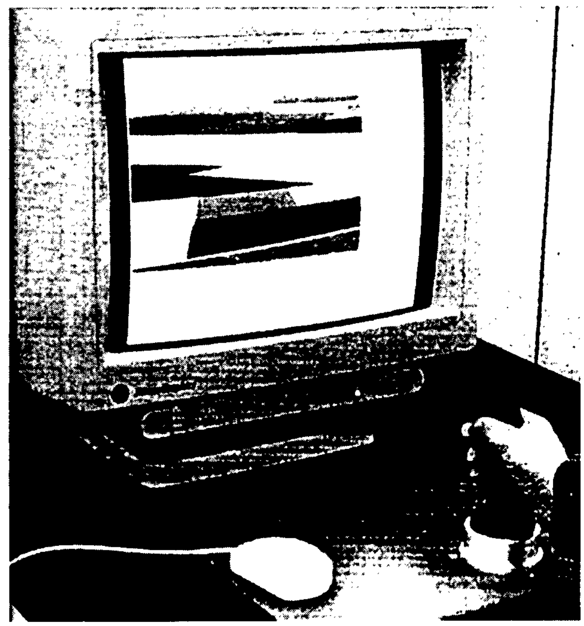


Figure 3: Operator's workingplace and view to the simulated landscape

During the experiment a series of attack runs will be made with different starting points and directions and scenarios of target arrangements. The subject has to watch a group of targets (4 to 6) until one target appears coloured. The moment of colouring is the command to perform the target designation task ("lock on" and correcting aiming point). The subject is encouraged to bring the coloured target approxemately into the display center as soon as possible, press the lock-on button as quick as possible, and then correct the aiming point for target center. In the first test sections (blocks of 8 runs) during the experimntal procedure the scenarios are chosen so that the target to be selected also remains the final one. Later sections make it necessary to change the selected target. This means that a "locked-on" target shortly afterwards proves to be no longer relevant so that a new target designation has to be performed. This reflects the situation beeing expected in the real system that decisive recognition cues for the target often will be seen very late by the operator and firstly a prliminary lock-on is made to an object that is expected to be the target.

7. DEPENDENT AND INDEPENDENT VARIABLES

Independent Variables

During the examination of the operator's activity while performing the target designation task, various independent variables have to be varied as paramertes. So, as the first independent variable three different types of control sticks are prepared for comparison: (1) a moveable displacement stick and (2) a stiff or hybrid force stick and a (3) pure force stick. All sticks have handles of the same design. The moveable stick can be deflected in all directions to about 25° and is spring-centered. The so called hybrid force stick allows small deflections of about 5°, but the force values are the input signals.

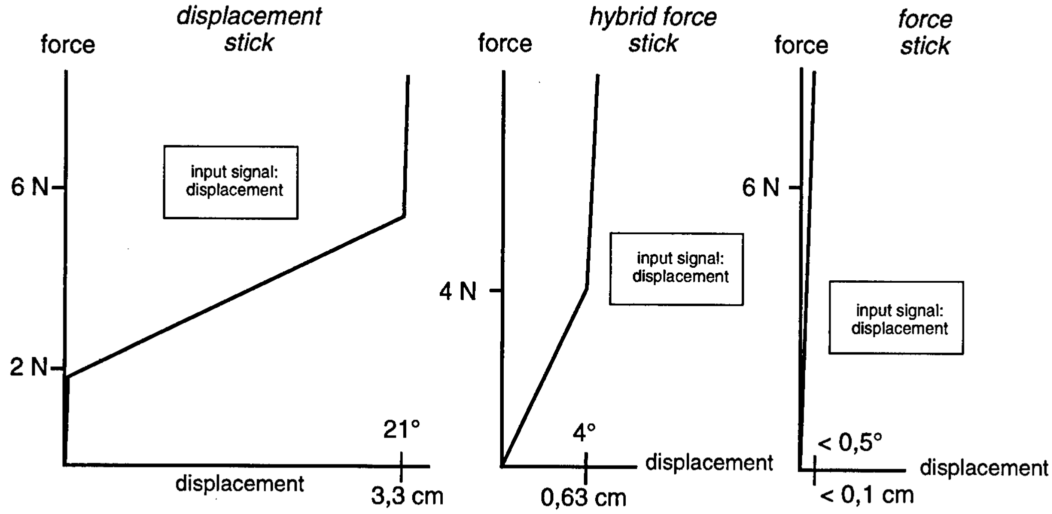


Figure 4: Force-displacement relationships for the three sticks

However, the small displacement has the essential advantage that the operator senses when the mechanical stop is reached, which corresponds to the maximum input signal point and signals that further force inputs do not result in a further increase of the input signal. Sensing of the maximum input signal point would not be possible when using the completely stiff force stick which has no mechanical stop. The force-displacement relationships for the three sticks are shown in figure 4

For the second independent variable the gain of the input signal is varied in three conditions: (1) normal, (2) high and (3) non-linear as a combination with a progressive transition from low gain for small input signals, to high gain for strong input signals. The low gain condition (1) enables camera turn rates of 4°/s by full deflection of the stick. The high gain condition (2) enables camera turn rates three times higher. For the non-linear gain condition (3) a function is calculated in which the signal of the low (linear) gain and the double of its squared values are added, so that a gain with small deflections of the stick is similar to the condition with low gain, while with strong stick deflections increasingly higher speeds of camera turn rates are reached up to 12°/s at full deflection of the stick. The three control gain conditions are illustrated in figure 5.

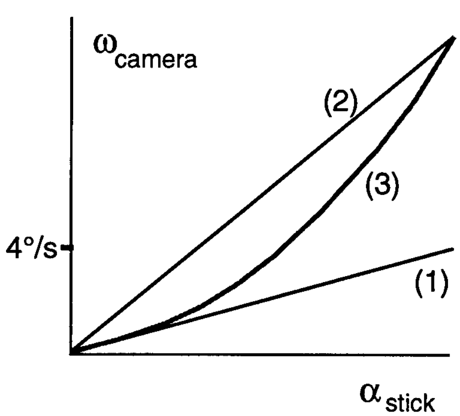


Figure 5: control gain

(1) normal
(2) high,
(3) nonlinear

For experimental reasons, (that means varying task parameters,) the effects of *recognition distances* are investigated. The distances at which a reliable target recognition can be expected, are varied in three steps: (1) distant: 1400 m and 1300 m, (2) medium:1200 m and 1100 m and (3) close: 900 m. In the experiment recognition is forced by colouring the relevant target at the distances subsumed. It is expected that the time demand for the target designation procedure increases with decreasing distances because of the increasing task difficulty due to a lack of time and quicker movements of the elements on the screen.

Dependent Variables

For the evaluation of the target designation task, the most important factor determining the operator's performance is the indication of the time needed for target designation. First of all the *time for lock-on*, i. e. the time difference between the moment of the target being coloured and the moment of pressing the "lock-on" button is the main performance indicator. Secondly, the time needed for correcting the aiming point is of interest. Moreover, the deviation of the aim point from the target center can be used as a performance measure for the target designation procedure. In addition, the subjective rating of the task difficulty will be assessed by means of the sequential judgement rating scale [5].

8. RESULTS AND CONCLUSIONS

The experiments are still in progress at the moment. However, some results and trends respectively already have become apparent. Final result presented in this paper are only concerned with aspects of control gain as shown in figure 5, done with one stick characteristic (hybrid force) of figure 4.

First of all, two results of previous pilot experiments will be discussed. The first one refers to an important

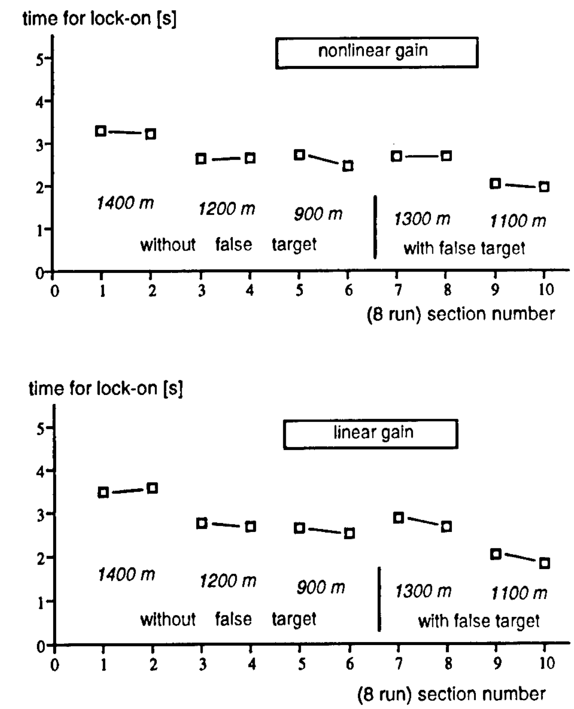


Figure 6: Results comparing linear and nonlinear control gain (two groups of subjects, 11 each.)

detail in the operational procedure, namely the transition from the manual control of the camera to the automatic target tracking phase by the tracker of an image processing system. Immediately after pressing the "lock-on" button, the input signal of the control stick has to be disabled for a certain period of time so that no possibly remaining control stick signals can work as unintended corrections for the aim point. It was shown that 0.5 s for this time period was completely sufficient. The second experimental result concerns the gain reduction after "lock-on". As the target is kept in the center of the screen, only low gain is necessary to adjust the aiming point. Gain reductions were varied in the pilot experiments between ratios of 1 : 2 and 1 : 10 with regard to the gain in the "camera direction control" mode. The ratio of 1 : 5 proved to be most controllable.

Estimations concerning the maximum time requirements of the target designation procedure can be drawn from pilot experiments as well as from the still incomplete current experiment. According to them, it was noticed that 95 % of all target designations needed less time than 2.4 seconds.

When comparing the three sticks, first evaluations showed no trends for differences of the operator's performance on target designation during the task applied.

The results available to date show massive disadvantages for the high control gain (2) of figure 5. This appeared already during the pilot experiments. As a consequence, high gain was omitted for further investigation and a test series was done to compare linear gain (1) and nonlinear gain (3) thereby using the hybrid force stick. 22 soldiers served as subjects. They were divided into 2 groups, a nonlinear gain group and a linear gain group. All subjects at first performed 6 sections (blocks of 8 runs) without false targets and then 4 sections with false targets as mentioned earlier.

The times for lock-on as group means per section over the current section number are shown in figure 6. The predominant tendency for the decreasing length of time while increasing the section number reflects mainly learning of the subjects. The group means in section 10, i. e. the last 8 of 80 attack runs, reach values of 2.1 s and 2.0 s respectively with no significant difference between nonlinear and linear control gain. Because of the covering by learning none of the expected influence of recognition distances on the time for lock-on could be established.

Evaluation of the time needed for correcting the aim point proceeded with some difficulties, because subject tended to lengthen their corrections until end of attack, thus covering the real deadline of correcting activity necessary. However correcting time on average can be estimated that they do not exceed 3 seconds.

Subjective ratings revealed a trend (but without significance) showing less task difficulty for the nonlinear control gain group. High intra-individual variances of the ratings were observed. Altogether it appeared that the task could be easy performed by the subjects. From this and considering the relatively short times for lock-on it can be derived that successful target designations are likely to be performed until recognition distances of nearly 700 m.

Alternative cursor control influences (indirect camera control) are reserved for future experimental series. Another aspect to be looked at in further investigations additionally will by the use of a camera with two different fields of view that can be switched by the operator.

9. REFERENCES

1. Howland, D. and Noble, M.E., "The effect of Physical Constants of a Control on Tracking Performance", J.Experimental Psychology, *46,* 5, December 1953, pp 353-360.

2. Magdaleno, R. E. and McRuer, D. R., "Effects of Manipulator Restraints on Human Operator Performance", USAF Flight Dynamics Laboratory, Tech. Rept. TR-66-72, 1966

3. Krüger, W. and Gärtner, K.-P., "Aspekte der Eingabecharakteristik von Bedienelementen zur manuellen Regelung", *in* "Spektrum der Anthropotechnik: Beiträge zur Anpassung technischer Systeme an menschliche Leistungsbereiche", Forschungsinstitut für Anthropotechnik, Wachtberg-Werthhoven, 1987, (ISBN 3-980-09704-8), pp 203-211.

4. Krüger, W., "Nichtlineare Bediensignalverstärkung bei einer Folgeregelaufgabe", Zeitschrift für Arbeitswissenschaft, (Verlag Dr. Otto Schmidt KG, Köln,) *37,* 1, January 1983, pp 45-50.

5 Pitrella, F.D. and Käppler, W.-D., "Identification and Evaluation of Scale Design Principles in the Development of the Sequential Judgement. Extended Range Scale", Bericht Nr. 80, Forschungsinstitut für Anthropotechnik, Wachtberg-Werthhoven, Germany, 1988

CRESUS

CHARGE RADAR EMBARQUEE SUR U.A.V. DE SURVEILLANCE

RADAR PAYLOAD FOR SURVEILLANCE U.A.Vs

Frédéric PERRET
THOMSON-CSF Applications radar
6, rue Nieuport - BP 86
78143 Vélizy-Villacoublay Cedex
France

Jean-Michel HERMER et Thierry GACH (THOMSON-CSF Radars et Contre-Mesures)
Emmanuel SICSIK-PARE (DGA, Direction des Systèmes de Forces et de la Prospection)

SOMMAIRE

L'utilisation d'un radar permet de résoudre les problèmes rencontrés par les systèmes optiques ou infrarouges initialement installés sur drone par mauvaises conditions météorologiques.

Au titre d'un contrat DGA passé en 1994, THOMSON-CSF a développé un démonstrateur d'un futur radar bi-mode SAR/MTI de surveillance du sol sur drone lent.

Après avoir rappelé le besoin opérationnel (chapitre 2) et la méthodologie de conception de CRESUS (chapitre 3), les grands choix effectués pour CRESUS sont explicités (chapitre 4), en particulier celui de la moyenne portée qui permet non seulement de résoudre le problème tous temps, mais également de bénéficier au maximum des capacités intrinsèques du radar, à savoir sa capacité à percer les couches nuageuses et donc à observer de plus haut et de plus loin.

Dans la suite, sont présentés les traitements MTI et SAR (chapitre 5), les performances et les caractéristiques (chapitre 6), les descriptions physique et fonctionnelle (chapitre 7) ainsi que la station d'exploitation au sol (chapitre 8).

La conclusion (chapitre 9) souligne l'évolutivité du démonstrateur permettant d'y adjoindre à moindre coût un mode SAR très haute résolution ainsi que la modularité du radar final permettant de l'installer sur différents types de drones (drones tactiques, drones MALE, ...).

SUMMARY

Under a contract awarded in 1994 by French MOD (DGA), THOMSON-CSF has developed a demonstrator for a SAR/MTI Air-Ground Surveillance radar on low speed UAVs.

After having explained the operational requirement (part 2) and the method used to develop CRESUS (part 3), the principal choices made for CRESUS are explained (part 4), especially the choice of a medium range. This range enables one to take advantage, at the maximum possible extent, of the intrinsic features of a radar, that is to say its capability to look through the clouds and, as a direct consequence, its ability to observe from a higher and farther position.

A description of MTI and SAR signal processings (Part 5), performances and characteristics (part 6), a physical and functionnal description (part 7) and a description of the ground segment (part 8) are then given.

The conclusion (part 9) emphasizes the versability of the demonstrator since it can be improved, at low cost, by adding a high resolution SAR mode. Furthermore a low cost installation of the final radar on different classes of UAVs (tactical, MALE, ...) is possible.

Paper presented at the AGARD MSP Symposium on "System Design Considerations for Unmanned Tactical Aircraft (UTA)", held in Athens, Greece, 7-9 October 1997, and published in CP-594.

1. INTRODUCTION

L'utilisation d'un radar permet de résoudre l'inconvénient majeur présenté par les systèmes de surveillance initialement installés sur drone (systèmes optiques ou infrarouges) : leur inefficacité par mauvaises conditions météorologiques.

Le radar CRESUS, conçu par THOMSON-CSF pour répondre au besoin de l'Armée de Terre a fait l'objet d'un développement exploratoire au titre d'un contrat passé en 1994 avec les services techniques de la DGA (SPOTI).

CRESUS est un radar bi-mode SAR/MTI, destiné à être embarqué sur un drône lent, de type BREVEL, CRECERELLE, SPERWER, ... Il constitue une base pour la réalisation de radars opérationnels pouvant équiper des hélicoptères ou drones légers tels que les drones MALE (Moyenne Altitude, Longue Endurance).

La réalisation du radar est terminée, les essais en vol débuteront en novembre 1997.

2. BESOIN OPERATIONNEL

La mission principale du système est l'acquisition du renseignement sur la zone divisionnaire avec une capacité tous temps. Le renseignement concerne la progression et le déploiement d'unités adverses ou amies. Le système doit compléter les dispositifs stand-off (tel que le radar HORIZON développé par THOMSON-CSF), aux endroits où ils sont masqués par le relief.

Le profil de mission est un profil en pénétration ou en stand-off. La fauchée est suffisante pour permettre un profil de mission simple.

Le radar doit détecter et localiser :

- les objectifs fixes dont le déploiement est caractéristique (PC en campagne, batteries de missiles Sol-Air ou Sol-Sol, colonnes de véhicules à l'arrêt, bases logistiques, ...),
- les véhicules terrestres mobiles (véhicules légers, véhicules lourds, véhicules blindés à roue, véhicules blindés à chenille),
- les hélicoptères mobiles et les hélicoptères en vol stationnaire.

3. CONCEPTION DE CRESUS

La conception d'un radar de surveillance est basée sur une décomposition fonctionnelle pour les spécifications des éléments physiques et du traitement algorithmique.

En effet, le grand nombre de paramètres et la complexité d'un radar nécessitent l'emploi d'une méthodologie pour maîtriser et spécifier de façon optimale ses fonctions.

D'une façon générale, le nombre de chaînes fonctionnelles utilisées est habituellement au nombre de quatre :

- la chaîne "mission" qui permet d'analyser les solutions en terme de performances temporelles d'une fonction,
- la chaîne "image" qui permet de définir les caractéristiques de la charge radar et du traitement algorithmique,
- la chaîne "exploitation" : stockage et accès aux données, post-traitement, analyse des images par des opérateurs,
- la chaîne "déssimination /interopérabilité".

Dans le cadre du démonstrateur CRESUS, seule la chaîne "image" est concernée.

Les objectifs principaux de l'emploi de cette chaîne "image" sont de spécifier de façon complète et précise les paramètres de fonctionnement du radar (bande, fréquence de récurrence, puissance de l'émetteur), ainsi que les caractéristiques des sous-ensembles (antenne, pilote, émetteur, récepteur, ...) en évitant en particulier les sur-spécifications, souvent très couteuses.

Après la définition de la chaîne "image", la démarche comporte trois grandes étapes :

- l'établissement des paramètres (forme d'onde, fréquence de récurrence, pondérations de l'antenne, ...) de la chaîne "image" décrivant chaque fonction. L'objectif est de préciser les fonctionnalités de haut niveau de cette chaîne fonctionnelle,
- l'étude et l'analyse de l'influence sur les performances, des imperfections des élément physiques : mouvements du porteur, imperfections de la chaîne émission/réception, ...
- la validation des résultats obtenus par rapport aux performances demandées. Une partie de ces validations sont effectuées par le biais d'outils de simulation.

Plusieurs itérations sont bien sûr nécessaires pour converger vers les paramètres de la fonction et les caractéristiques des sous-ensembles du radar.

4. LES GRANDS CHOIX

4.1 Portée - Fauchée

La portée du radar CRESUS est de la classe moyenne portée.

Cette classe de portée, compatible d'un emport sur drone, permet d'exploiter de façon optimale, les caractéristiques intrinsèques des radars :

- leur capacité à observer beaucoup plus loin que les systèmes optiques ou infrarouges,
- leur faible sensibilité aux variations météorologique leur assurant une capacité tous temps mais aussi celle de percer les couches nuageuses et donc d'observer de plus haut.

Les avantages qui en découlent sont :

- une capacité de surveillance nettement accrue en terme de surface surveillée et de capacité tout temps,
- une vulnérabilité réduite dans la mesure où cette surveillance est effectuée à haute altitude et sans avoir à survoler les zones surveillées pouvant être fortement défendues,
- des conditions d'emploi simplifiées en terme de préparation de mission et de profil de vol,
- une capacité secondaire de surveillance stand off, permettant en particulier une utilisation en temps de paix pour le contrôle de zones frontières.

4.2 Fréquence

Les avantages des hautes fréquences sont :

- intégration plus aisée (technologie hyperfréquence plus compacte),
- en mode MTI, à dimension d'antenne donnée, meilleure visibilité des cibles lentes,
- en mode SAR, à résolution transverse donnée, temps d'intégration plus court et accélérations résiduelles acceptables plus élevées.

L'inconvénient majeur des hautes fréquences est constitué par les pertes de propagation par mauvais temps (pluie, brouillard, couches nuageuses).

La bande de fréquence du radar CRESUS est donc la bande Ku qui réalise le meilleur compromis.

4.3 Visée latérale

Les avantages de la visée latérale sont :

- hautes performances en portée et fauchée (taille d'antenne supérieure),
- en mode MTI, bonnes performances de détection des cibles lentes sans traitement complexe,
- antenne conforme facilitant l'intégration sur différents types de porteur.

Le radar CRESUS est donc un radar à visée latérale.

En mode SAR, la visée latérale est orthogonale à l'axe du drone. Ce type de visée est optimal, car il permet de réduire les temps d'intégration nécessaires.

En mode MTI, la visée latérale est oblique vers l'avant du drone. Ce type de visée permet d'une part, un profil de mission qui longe les axes routiers, et d'autre part, d'indiquer au mode SAR les zones de forte activité.

4.4 Antenne et asservissement

L'antenne du radar CRESUS est une antenne conforme, bi-mode (SAR/MTI), à guides à fentes.

L'ouverture en site est dimensionnée de façon à prendre en compte les mouvements de roulis et de tangage du drone.

En mode SAR, l'ouverture en gisement est suffisamment importante pour prendre en compte les mouvements de lacet pendant le temps d'intégration. Ceci est compatible de la moyenne portée en raison du gain d'intégration important de ce mode.

En mode MTI, l'ouverture en gisement est suffisamment faible pour atteindre des performances satisfaisantes en terme de portée et de vitesse minimale détectable.

L'éclairement de la cible pendant le temps d'observation est assuré par balayage électronique un plan, réalisé par l'utilisation conjointe d'une antenne dispersive en gisement (antenne à guides à fentes à ondes progressives) et d'agilité de fréquence.

4.5 Entrelacement SAR/MTI

Dans le radar CRESUS, les modes MTI et SAR sont entrelacés temporellement.

L'entrelacement utilisé permet une couverture continue du terrain dans les deux modes SAR et MTI, sans qu'aucun des deux modes n'ait ses performances altérées par la présence de l'autre.

4.6 Architecture

Traitement de signal :
Pour respecter les contraintes de débit de la transmission de données (4 Mbits/s), l'architecture retenue est la suivante :

- traitement MTI effectué en temps réel à bord,
- prétraitement SAR à bord et traitement effectué au sol.

Capteurs de mouvement :
De façon à être autonome du porteur, le radar CRESUS est équipé de ses propres capteurs de mouvements :

- trois gyromètres donnant le lacet, le roulis et le tangage,
- trois accéléromètres donnant les accélérations sur les trois axes orthogonaux,
- un GPS donnant principalement la position, la vitesse sol et la route.

4.7 Adaptations adoptées pour le démonstrateur

Ces adaptations ont consisté à adopter des solutions moins onéreuses que celles du radar final, sans réduire l'aspect démonstratif.

C'est pourquoi, elles ne portent que sur des aspects techniques maîtrisés par ailleurs.

- Porteur :

Pour le démonstrateur, le porteur utilisé est un porteur de servitude (hélicoptère léger Gazelle) possédant des caractéristiques de vol (vitesse, altitude) voisines de celles du drône final.

- Antenne :

Pour le démonstrateur l'antenne conforme bi-mode SAR/MTI est remplacée par deux antennes plates superposées.

- Transmission de données :

Pour le démonstrateur, il n'y a pas de transmission de données en temps réel. Les données sont enregistrées à bord sur disque dur amovible, avec un débit d'enregistrement inférieur à celui de la transmission de données envisagée pour le radar final (4 Mbits/s).

- Fauchée SAR :

Pour le démonstrateur la fauchée SAR instrumentée est réduite d'environ un facteur quatre, pour limiter la puissance de calcul nécessaire.

- Encombrement :

Seule les contraintes de masse (20 kg) et de volume (25 l) portant sur la chaine hyperfréquence (chaîne pilotée, émetteur et récepteur) sont conservées.

5. TRAITEMENTS

Le traitement de signal implanté dans le radar CRESUS est basé sur l'expérience reconnue de THOMSON-CSF dans le domaine, démontrée en particulier à travers les réalisations des systèmes HORIZON et RAPHAEL.

5.1 Traitement MTI

Il est effectué en temps réel à bord.

L'exploitation est effectuée au sol sur un poste opérateur constitué de stations de travail standards.

Ce traitement comprend :

- un module de compensation des mouvements du porteur,
- un module de détection et de lever d'ambiguité des cibles mobiles (cibles terrestres et hélicoptères),
- un module spécifique de détection des hélicoptères en vol stationnaire,
- un module de localisation des cibles utilisant les informations délivrées par le radar et par les capteurs de mouvements spécifiques de CRESUS,
- un module de classification automatique basée sur les signatures Doppler des cibles. Cette classification utilise le dispositif de classification automatique DIRACH mis au point par THOMSON-CSF et implanté dans le radar HORIZON. Dans le cadre du démonstrateur, ce module, maîtrisé par ailleurs, n'est pas implanté.

5.2 Traitement SAR

Le traitement SAR est constitué d'un prétraitement embarqué ainsi que d'une formation d'image et d'une exploitation effectuées au sol sur le même poste opérateur.

Le prétraitement embarqué (filtrage et sous-échantillonnage) est destiné à réduire le débit de données.

Le logiciel de traitement SAR (codé en langage C) est implanté sur le poste opérateur.

Il est conçu de manière très modulaire, ce qui lui confère les avantages suivants :

- possibilité de sélectionner et/ou de combiner tout ou partie des modules déjà développés pour affiner le traitement ou au contraire privilégier la rapidité d'exécution,
- possibilité d'inclure de nouveaux modules et/ou de modifier les modules déjà existants d'une manière efficace et souple.

Les principaux modules implantés actuellement sont :

- analyse et correction des données brutes,
- compensation de mouvements basée sur les informations issues des gyromètres, des accéléromètres et/ou du GPS,
- calcul du Doppler moyen,
- correction des déphasages,
- autofocus,
- compression,
- suréchantillonnage des données d'un facteur deux par rapport à la résolution,
- visualisation comprennant des outils d'exploitation spécifiques à l'imagerie SAR comme des outils de détection de cibles.

D'autres modules peuvent être activés comme le multi-vues ou la correction radiométrique nécessitée par des mouvements éventuels du lobe d'antenne en azimut.

Ce logiciel est naturellement portable et fonctionne actuellement sur HP et sur SUN sous système d'exploitation UNIX.

6. PERFORMANCES ET CARACTERISTIQUES DU DEMONSTRATEUR

Ce chapitre présente, de façon synthétique, les performances et les caractéristiques du démonstrateur CRESUS.

La figure 1 schématise la zone éclairée de façon instantanée par le radar CRESUS.

6.1 Performances du mode MTI

+ Portée : moyenne portée.
+ Fauchée : classe 10 km.
+ Domaine vitesse : compatible des vitesses de vol des hélicoptères.
+ Résolution distance : classe 10 m.
+ Résolution vitesse : classe 1 km/h.
+ Précision de localisation : classe 100 m.
+ Détection des cibles terrestres.
+ Détection des hélicoptères, y compris stationnaires.

6.2 Performances du mode SAR

+ Portée : moyenne portée.
+ Fauchée : classe 3 km.
+ Résolution distance : classe métrique.
+ Résolution azimut : classe métrique.
+ Cartographie.
+ Détection des cibles fixes.

6.3 Caractéristiques

+ Bande de fréquence : Ku.
+ Bande d'agilité : classe 1 GHz.
+ Puissance émise : classe 100 W crête.
+ Débit de données : 4 Mbits/s.

7 DESCRIPTION DU DEMONSTRATEUR

7.1 Description fonctionnelle

La figure 2 présente le synoptique fonctionnel haut niveau du démonstrateur CRESUS.

Ce synoptique fait apparaître les sous-ensembles intégrés dans le POD et dans la baie, ainsi que ceux ne constituant que de l'instrumentation spécifique au démonstrateur, destinés à être remplacés dans le radar final par une transmission de données temps réel.

7.2 Description physique

Le démonstrateur comprend trois sous-ensembles principaux notés A, B et C :

- le POD (A), fixé sur le bras d'arme de la Gazelle, en lieu et place des missiles HOT,
- la baie d'exploitation (B), intégrée dans la cabine de la Gazelle,
- la station d'exploitation au sol (C).

Le POD (A) contient ou supporte (figures 3 et 4) :

- le coffret pilote/récepteur (A1),
- l'émetteur à TOP (A2),
- le prétraitement SAR (A3),
- le bloc alimentation (A4),
- l'aérien (A5) contenant l'antenne MTI (A51), l'antenne SAR (A52) et le bloc gyromètres /accéléromètres (A53).

La baie d'exploitation (B) contient (figures 5 et 6) :

- le poste opérateur bord constitué par le moniteur couleur (B1) et le calculateur bord (B2). Pour le radar final, le poste opérateur bord sera remplacé par une transmission de données temps réel,
- le coffret traitement gestion (B3) contenant le module de gestion, le traitement MTI temps réel et le GPS.

La station d'exploitation au sol constituée par :

- un calculateur HP série 9000 J200 sous UNIX, sur lequel est implanté le traitement SAR,
- un calculateur SUN Ultra 1 sous UNIX, sur lequel est implanté l'IHM,
- un moniteur couleur 19 pouces haute résolution.

8. STATION D'EXPLOITATION AU SOL

L'exploitation des données acquises en vol est effectuée sur la station sol.

Deux écrans différents sont présentés à l'opérateur.

Le premier écran, à tendance MTI, contient principalement :

- une carte de sol numérisée sur laquelle sont représentées :
  - ⇒ la position des fauchées SAR et MTI,
  - ⇒ les cibles détectées en MTI (rapprochement, éloignement et hélicoptères stationnaires) avec leurs attributs (position, vitesse, SER, ...),
  - ⇒ la carte d'échos fixes.

  La figure 7 présente une illustration de cette carte.
- une carte SAR à résolution dégradée (classe décamétrique) permettant à l'opérateur de faire un premier tri des cartes à analyser plus finement dans le second écran

Le second écran, à tendance SAR contient principalement la carte SAR à pleine résolution, avec la mise à disposition d'outils automatiques d'aide à l'interprétation (seuillage) et à la détection (détecteur à taux de fausse alarme constant). La figure 8 présente une illustration de cette carte.

9. CONCLUSION

Au titre d'un contrat DGA passé en 1994, THOMSON-CSF a développé le radar CRESUS, démonstrateur d'un futur radar bi-mode (SAR/MTI), destiné à être intégré sur un drône tactique lent de type BREVEL, CRECERELLE, SPERWER, ...

La description, les performances et les caractéristiques du démonstrateur ont été présentées dans les chapitres 4 à 8.

Le choix d'une antenne latérale bi-mode conforme permet à terme une intégration de CRESUS sur différents types de drones.

Les essais en vol du démonstrateur auront lieu à partir de novembre 1997 sur un porteur de servitude (hélicoptère léger Gazelle).

Des évolutions sont d'ores et déjà prévues sur le démonstrateur. La plus importante concerne l'implantation d'un mode SAR à très haute résolution (classe sub-métrique) permettant de renforcer la détection des cibles fixes isolées tout en rendant possible leur reconnaissance. Les travaux correspondants ont débuté par une simulation (contrat DGA) dont l'objectif principal est de définir la résolution nécessaire pour satisfaire le besoin.

Cette simulation est réalisée à l'aide de l'outil logiciel SARCM développé par THOMSON-CSF. Cet outil permet de générer des données brutes conformes aux caractéristiques des sous-ensembles du radar, donc représentatives de celles qui seront réellement acquises par le radar. La validation du traitement est effectuée sur l'algorithme SAR qui sera réellement utilisé dans le segment sol de CRESUS.

Après cette phase de simulation, les travaux se poursuivront par l'implantation de ce mode dans le démonstrateur. Cette implantation ne nécessitera qu'un minimum d'évolutions du matériel, dans la mesure où cette évolution a été prise en compte dès la conception.

D'autre part, l'augmentation de la portée pouvant être obtenue par l'augmentation conjointe de la dimension d'antenne et de la puissance émise, permettra à CRESUS de satisfaire le besoin opérationnel dévolu aux drones MALE (Moyenne Altitude - Longue Endurance).

FIGURE 1

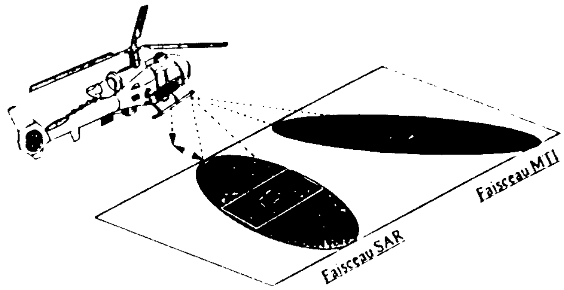


FIGURE 2

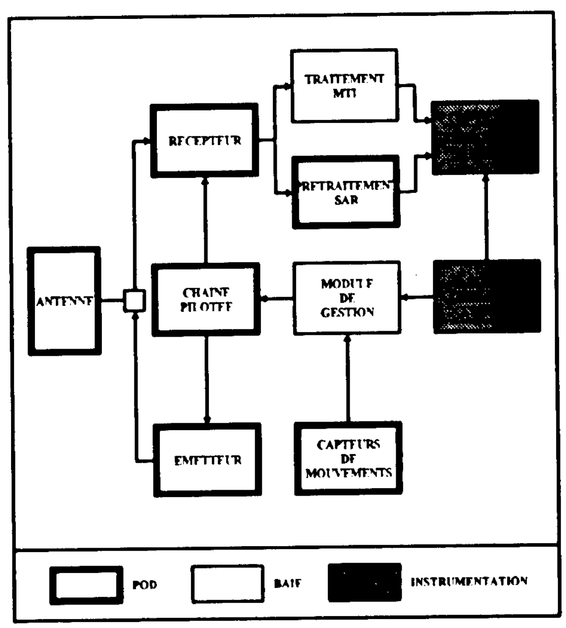


FIGURE 3

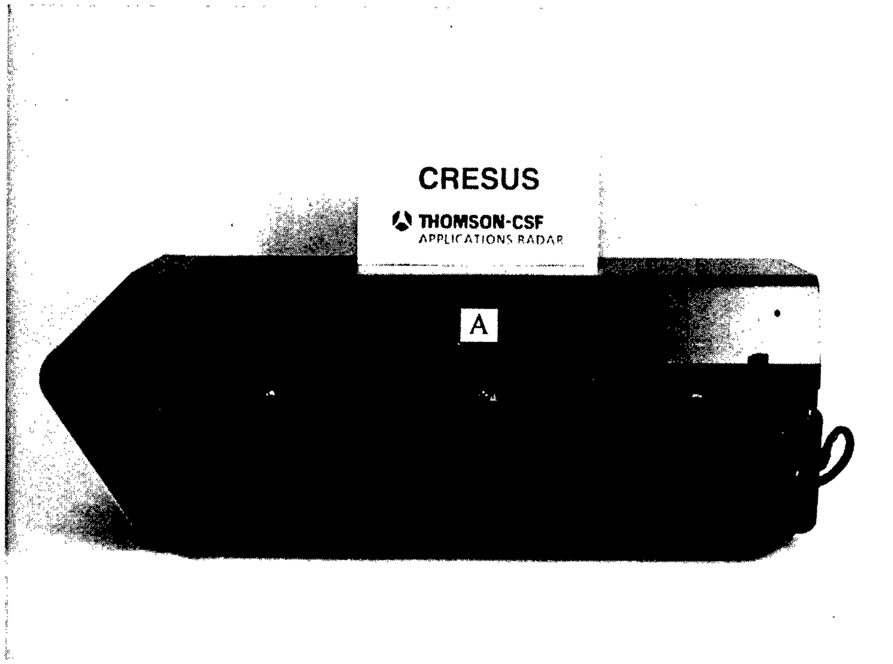
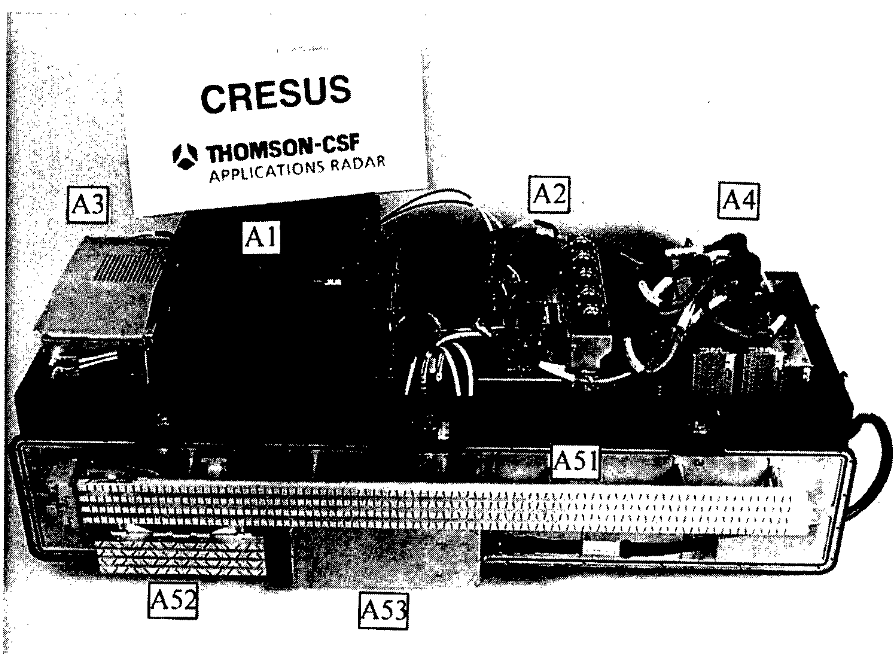


FIGURE 4



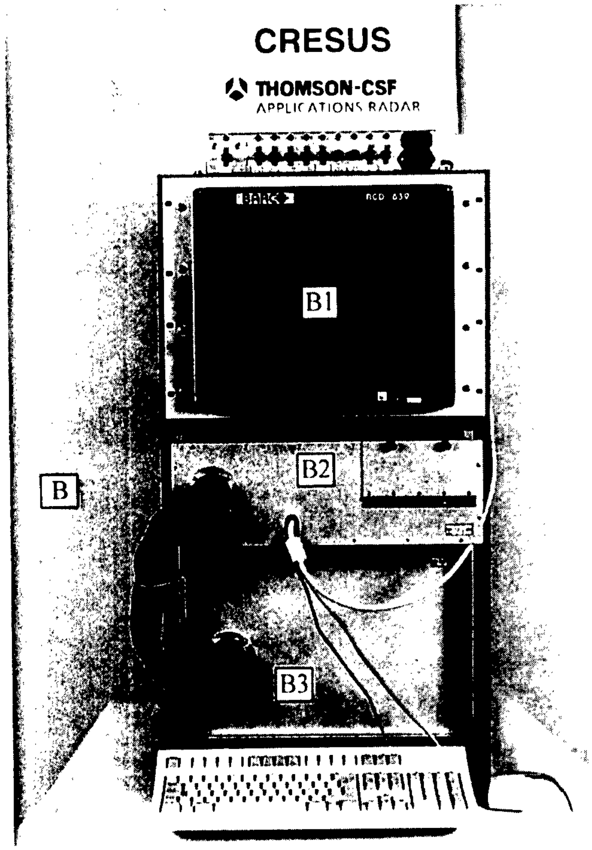


FIGURE 5

FIGURE 6

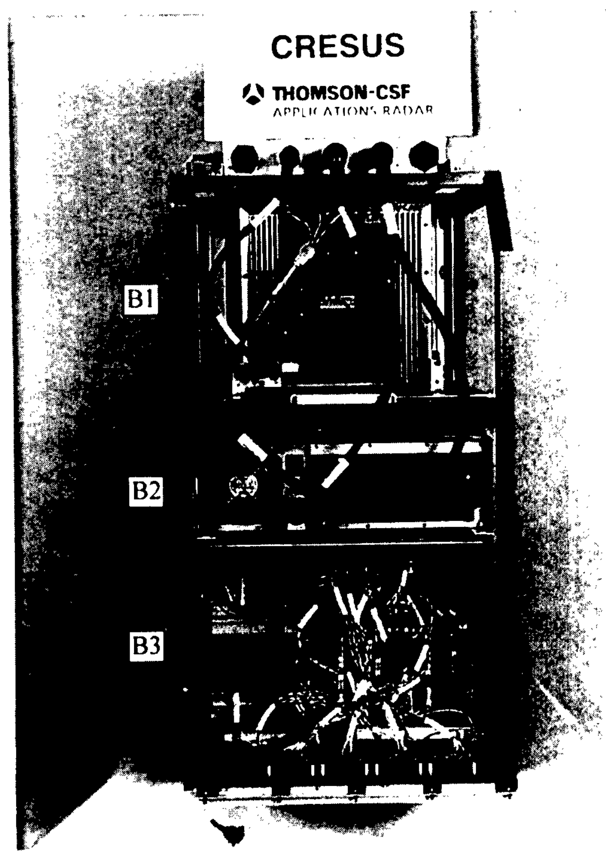


FIGURE 7

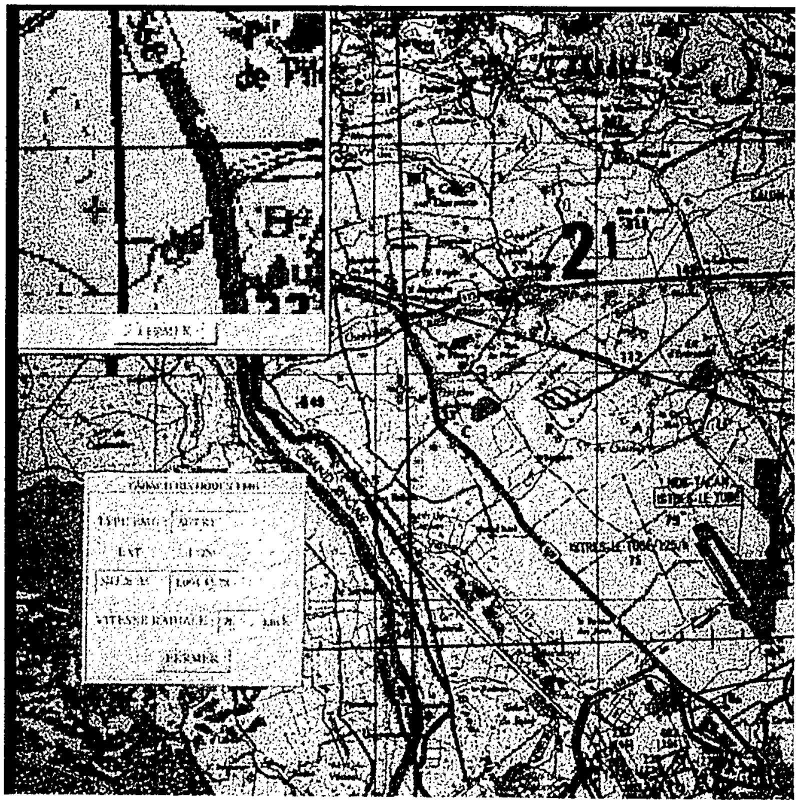
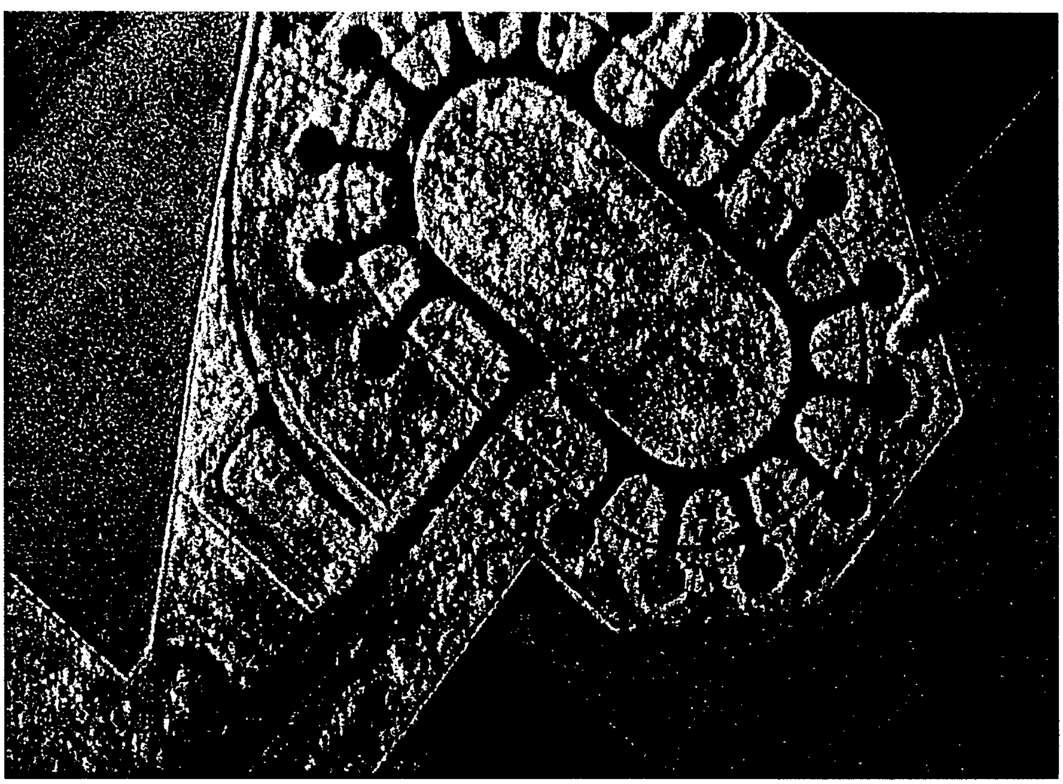


FIGURE 8



Layered Fault Tolerant Architecture to Support Context-Sensitive Reasoning for Lethal Unmanned Aerial Vehicle Application

Jennifer Rau
Johns Hopkins University Applied Physics Laboratory
Johns Hopkins Rd.
Laurel, MD 20703
301-953-6296(ph), 301-953-5928(fax)
raujl1@central.ssd.jhuapl.edu

1. INTRODUCTION

The Johns Hopkins University Applied Physics Laboratory (JHU/APL) has designed a processor architecture which provides fault tolerance for real-time vehicle applications and which supports high-level context-sensitive reasoning. The design employs a layered approach combining a low-level network with a supervisory top-level processor architecture to provide processing power to support high-level reasoning and embedded control of subsystem functions. This dual-level architecture approach supports capabilities such as subsystem status reporting, node monitoring, vehicle diagnosis, reallocation of control in response to failures, consistency of data, data fusion, and synchronization of system states. In addition to the processor architecture, a software architecture was defined for lethal Unmanned Aerial Vehicle (UAV) application which merges the required functionality of the lethal UAV software with the capabilities of the processor/communication architecture to support improved mission effectiveness, survivability, and vehicle fault tolerance.

The layered processor architecture was designed to provide fault-tolerant distributed processing and subsystem communications for autonomous vehicle application. Several alternatives were examined, and the resulting design considered not only the technical requirements/performance but also constraints such as cost, size, weight, commercial availability, flexibility, and adherence to standards. Salient features of the architecture include: distributed control, distributed data, dynamic reallocation of processes to recover from hardware and software failures, communications between subsystems and software applications, elimination of single point failures, and isolation of the vehicle architecture from subsystem changes (payload, weapon, communication, etc.). The communication utilities required to support these functions were developed and tested. The utility modules include the following functions; message passing, location transparent routing, node/application monitoring, node/application recovery, and data distribution/validation. These functions support the optimization of processor capabilities and graceful degradation of the vehicle's reasoning functions.

Many existing systems use similar utilities including manned air vehicles and unmanned underwater vehicles [UUV's, see Reference (1)]. However, fault tolerance is very closely coupled to a specific vehicle design. The design of subsystem communications network architecture, data content/format, processor architecture, communications utilities/protocol features, etc. will be specific to an individual vehicle and the related mission and requirements (i.e. a lethal autonomous vehicle will require a different approach and level of fault tolerance than a manned vehicle). Because of this close coupling between a specific application and the incorporation of fault tolerance, it can be difficult to integrate fault tolerant features into an existing design. This paper concentrates on fault tolerance for lethal UAV application and applies off-the-shelf technology in a flexible architecture to simplify integration.

The defined architecture provides a capable and reliable communication network for the implementation of context-sensitive reasoning. Functions critical to lethal UAV effectiveness such as sensor management, vehicle management, weapon management, position monitoring, maneuver control, and mission planning can all be based on the most current vehicle, mission and subsystem status. Reliable subsystem communications provide vehicle and sensor data to a high-level processor architecture which maintains a consistent and accurate data store on which reasoning can be based. This data can be maintained as a source for payload, weapon and adaptive vehicle management decisions. A preliminary architecture identifying the integration of lethal UAV software functions which builds on the capabilities of the processor/communication network is addressed.

2. DESIGN

The selected architecture combines aspects of more than one approach, while weighing affordability of components, flexibility, availability, size/weight, operating efficiency, and added system complexity against the desirable features to ensure a low-risk and practical design which has significant application potential. The proposed architecture is a layered approach using both Local Area (LAN) and Local Operating Networks (LON) [see Reference (2)]. Dual gateways or access points are established between the networks to provide for message passing from one network type to another. The LAN is applied between capable processors for main processing functions such as system optimization, vehicle control, mission planning, and fault diagnosis/handling. The embedded processor nodes provide processing for subsystem control functions (i.e., motor, actuator, sensors) and communication between subsystems.

The high-level processing architecture is designed to distribute supervisory functions, support context-sensitive reasoning, and enhance processor reliability (an excess of processing power which can be used in the event of processor failures). Even as single-board processor capabilities expand, system reliability requirements necessitate the use of multiple hardware components. Since many autonomous vehicle applications have critical response time limitations (specifically UAVs), application of AI techniques to meet time response requirements still requires multiple processors. Given additional size, weight and design complexity factors, optimization of onboard processing power provides an improvement over the use of strictly redundant components.

In order to provide graceful degradation of system performance relative to failure of processors in the high-level layer, there are several communication protocol features to be applied. These include: transparent reallocation of software applications, routing of messages mapping physical to logical addresses, node diagnosis to determine processor failures, monitoring network for communication failures, centralized/distributed data to support restarts and reallocation of applications, and message passing at the application level. Use of a standard protocol such TCP/IP which is also available for bus communications enables the application of this architecture using both a dual LAN or a single LAN and VME bus running TCP/IP. Figure 1

Paper presented at the AGARD MSP Symposium on "System Design Considerations for Unmanned Tactical Aircraft (UTA)", held in Athens, Greece, 7-9 October 1997, and published in CP-594.

shows both alternatives with dual connections to nodes which provide access to the subsystem network.

To eliminate single-point failures, there must be multiple communication links with multiple network access for each processor. This provides unaffected operations in the event of a network failure or a network interface failure. The dual network is implemented with both networks being active. Identical messages are broadcast over both networks such that switching to the alternate network does not require dynamic reconfiguration. Message passing over the network will support not only application-specific interprocess communications, but the passing of application variables necessary to restart an application without significant loss of state. The periodicity of variable passing will be used to identify the status of processor nodes. A status monitoring utility will maintain a table of communication status for each node. Continual polling of this will identify nodes which are not maintaining communications. For nodes which have exceeded the expected communication threshold, a status query will be initiated to verify communication failures, with both networks being monitored for response. In the event of a failure, recovery procedures will be initiated. For a communication link failure, a message will be sent to all processor communication software to identify which network should be considered as primary for retrieving messages. For a processor failure, the applications which were allocated to that processor are restarted on the remaining processor with the most available CPU time.

The subsystem network applied was based on a commercially available set of chips which provide LON features supporting subsystem status/control message passing, direct subsystem communications, network monitoring and reporting [Reference (2)]. The neuron chips provide both processing capabilities for subsystems and off-the-shelf communication protocol to provide subsystem networking. The integration of these nodes into an autonomous vehicle can include using them as embedded controllers within the subsystem (i.e., motor controller) or the use of the nodes solely to provide communication capabilities for the subsystem. The associated communications protocol provides reliable message-passing features both between nodes and to the parent/supervisory processor architecture. Each subsystem includes a minimum of two nodes to provide dual access to the network to minimize impact due to a node failure. A self-healing ring configuration [see Figure 2 and Reference (3)] provides for recovery from any single communication link failure. A similar low level architecture could be developed using embedded controllers with custom developed communications protocol software.

In keeping with maximizing the use of commercial components, communication between the LAN and subsystem network could be either through a commercially available gateway or through the use of host-to-neuron chip software [see Reference (4)]. The gateway listens in on the subsystem network activities and passes network variables onto the LAN. Since applying one gateway would instill a single-point failure, the architecture contains at least two passage points between the high and low level networks. Use of dual gateways needs to be examined to develop an approach for either designating one active at a time, or handing the redundancy of message passing which would occur by having them both active simultaneously.

In order for the layered processor architecture to be fault tolerant, there are several capabilities which need to be provided by the communications software. In order to recover from processor failures, dynamic reallocation of processes is required. To recover from network/ communication failures monitoring of the message traffic is necessary to determine network status. Software failures can cause interruptions in the processes capability to respond and therefore a warm restart capability is required to verify the necessity to reallocate an application to another physical processor. There are several more specific functions necessary to support these primary capabilities including: message passing, application based data stores containing restart variables; data validation; and location transparent routing. Since for autonomous vehicle application these communication capabilities are embedded as part of the onboard software, the implementation has been designed to minimize impact to performance. This section provides a detailed description of the communication utilities that were developed to support fault tolerant capabilities for distributed processing. Note that these utilities are not limited to autonomous vehicle application and the implementation is based on standard protocols (TCP/IP, UDP).

Each high-level processing node in the architecture will have resident communication utilities to support local applications. Figure 3 outlines the top-level processes and corresponding data flow necessary to support the identified capabilities. All the high-level processors in the architecture are connected via dual LAN connections. Messages from subsystems communicating via the local network are passed to the LAN through dual gateways. The gateway captures messages from the subsystem network, formats them appropriately and then puts the messages onto the LAN. Therefore, messages from all the vehicle subsystems and LAN messages from other software applications are available to the communication software on each processor. In addition, the message queue structure supports local communications between applications resident on the same processor. A library of message passing functions previously developed at JHU/APL were applied. This software provided routines for both retrieving messages from the network and obtaining messages from applications and sending them out over the network. Messages which are brought in are put into specific message queues for retrieval by application software. The message passing software uses TCP/IP and UDP protocols and is part of the functionality of the router. In order to provide dynamic reallocation of processes, several other capabilities were added to support the routing functions. The modules which comprise the communication utilities including the router, network diagnosis, network recovery, and application interface will be discussed in the following paragraphs.

Since processes/applications can be reallocated dynamically to other physical locations, the router must provide transparent message routing by maintaining a mapping of logical to physical addresses for both the high and low level networks. Since each application is expected to broadcast periodic state variables, the source of these messages can be used to validate the actual address of each application. The router reads messages from the network, verifies the source and destination and updates the address table as required sending out queries to resolve conflicts. Based on the destination, the messages are put into the appropriate queues where they are accessed by local applications. In addition to retrieving messages, the router accepts output messages from the applications, applies the proper physical address and sends it over the network. Each subsystem has dual nodes for subsystem network access with both active such that a failure will result in the subsystem switching to the data from the alternate node for processing. Single subsystem network connection failures are transparent to the high-level routing since the self-healing ring architecture provides alternate access for routing messages.

Messages for the communication utilities (i.e. responses and requests/queries) are available through the same message passing routines/queues. In order to reallocate processes and maintain communications, a process is required which continually monitors processor and network status to identify the necessity for reconfiguration. The network diagnosis process performs these functions in addition to handling state variables. State variables are periodically updated variables sent by each application such that a restart performed using

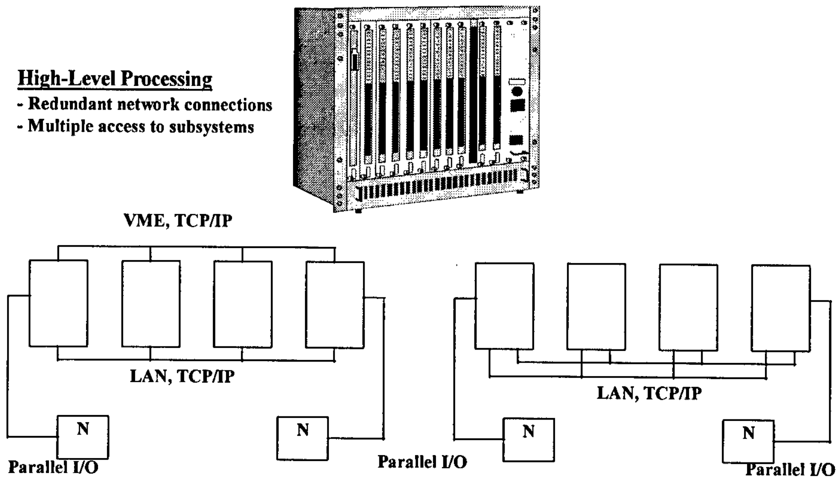


Figure 1 High-Level Processing Architecture

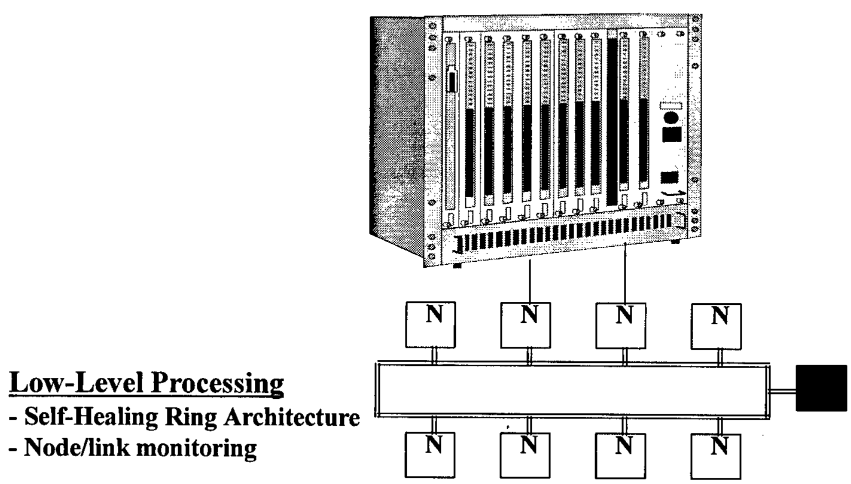


Figure 2 Subsystem Level Processing Architecture

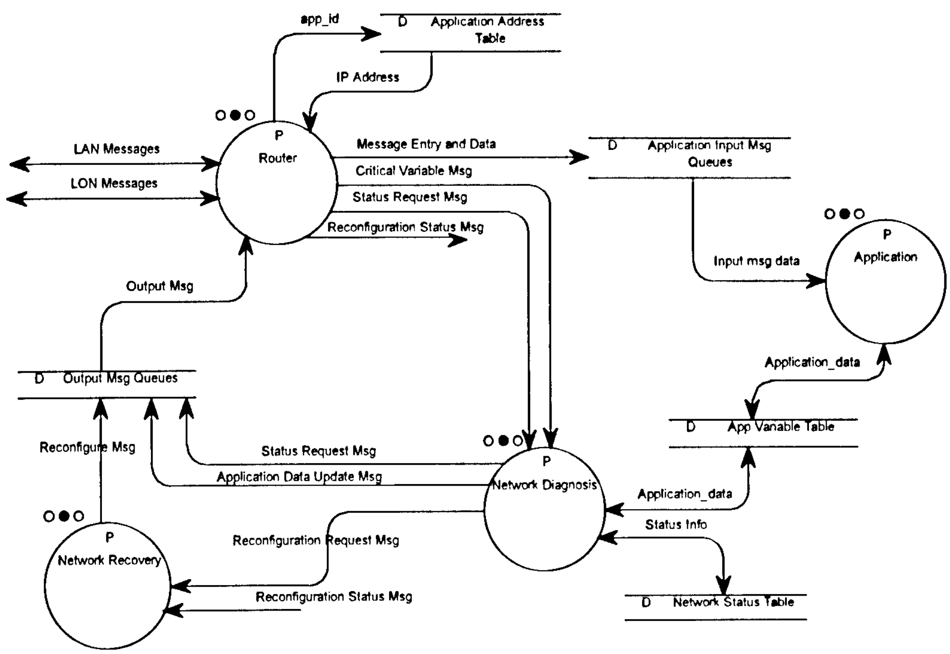


Figure 3 Communication Utilities

these values will continue the application from the last known state. The selection of state variables and the update rate is specific to the application. These variables are broadcast over the network and read by each of the processors such that local copies can be maintained. Since the periodicity of the state variables is known, it can be used to determine the proper functioning of an application and processor. State variable formats, value ranges and application owners are used to validate the data. The network status table is monitored to determine applications which have not provided state variables at the normal rate. This event initiates a status request message which will query a particular application concerning its status. If there is no response the application is assumed to have failed and queries are sent to the other applications co-located with the failed application to determine if it is an application software error or a processor failure.

After diagnosis, a failure message is provided to the network recovery process for handling. If it is just an application failure, a warm restart will be initiated based on critical variable values to attempt to restart on the same processor. If it is determined to be a processor failure, then the applications will be restarted on alternate processors. Even though every processor is running a network diagnosis process, only the processor with the lowest CPU utilization will be responsible for initiating recovery procedures. If that processor fails, then it will be marked as inactive and the remaining processor with the lowest CPU utilization will take over. The status of the processors and current CPU utilization for each is maintained as part of the network status table.

3. CONTEXT-SENSITIVE REASONING ARCHITECTURE FOR LETHAL UAV APPLICATION

The layered fault tolerant architecture provides a capable and reliable communication network for the implementation of context-sensitive reasoning. Functions such as sensor management, vehicle management, weapon management, position monitoring/maneuver control, and mission planning can all be based on the most current vehicle, mission and subsystem status. The processor architecture integrated into an air vehicle platform provides not only distributed processing, network communications between management software and subsystems, and processor fault tolerance, but also improved mission effectiveness. The architecture applies off-the-shelf technology for reliable subsystem communications providing both vehicle subsystem and sensor data to a high-level processor architecture which maintains a consistent and accurate data store on which reasoning can be based. The vehicle subsystem and sensor status information is maintained as a source for payload management, and adaptive vehicle management decisions. The design approach provides enough flexibility to support integration with any selected air vehicle platform. The extent to which access is provided for subsystem and payload information will depend on the specific sensors and the ability to adapt existing sensor/subsystem interfaces.

Figure 4 provides a conceptual software architecture for lethal UAV management functions. The reasoning functions will take advantage of the message passing process and communications protocol provided by the defined architecture. The design provides software modules with direct access to subsystem and sensor information. The subsystem, sensor, and application level information will be collected into a list of facts which trigger the firing of rules developed using an embedded rule-based language. This approach would provide mission decisions based on a defined set of rules and a dynamic set of facts (vehicle status, sensor data, communication data, current mission status, etc.) supporting context-sensitive reasoning and repeatable behavior.

Real-time on-board mission replanning would occur in response to failures, unexpected environmental conditions, vehicle safety concerns (i.e. collision avoidance responses, new airspace constraints) changes in information received via communications, resource limitations, or target/activity detection. The proposed approach includes defining mission events which trigger on-board replanning and specific response classes consistent with generic UAV capabilities. Input parameters most relevant to mission planning are to be identified relative to a specific mission set to bound the variables affecting reasoning. Since it is important to have consistent and predictable context-sensitive planning, a knowledge-based approach would be applied to support intelligent mission re-planning. The knowledge-based mission planner would interface with a path planner/checker to provide vehicle navigation guidance (intermediate waypoints, search paths, etc.), validation, and optimization of resources within identified constraints.

Mission management decisions are to be based on a combined set of data collected from messages received over the network. Further details of mission management functions are depicted in Figure 5. In addition to status information being applied for fault tolerance, sensor and subsystem messages would be combined with mission information and environmental parameters to provide a consistent tactical picture for optimizing mission effectiveness. Data sets are provided which contain a library of missions including the current mission, previously validated alternate missions, and an emergency mission. This supports the options of both autonomous planning to produce a revised mission real-time, or entry of predetermined alternate missions to be provided by the operator. Mission constraints, provided in the initial data set, identify parameters such as airspace constraints and vehicle dynamic limitations. Rule-based systems do not support the response time required for critical air vehicle situations such as collision avoidance or immediate airspace conflicts. Therefore, a maneuver manager is defined which would be implemented to optimize response time for providing an evasive maneuver for critical situations. The current vehicle position is continually provided and any requirement to evade is provided by the mission manager based on subsystem data or updated commands received via the datalink. Situations which may trigger an evasive action could include identification of air contacts, unexpected terrain limitations on vehicle flight or LOS communications, unexpected changes in airspace, etc. This module would also provide the maneuvers under emergency conditions which would lead the vehicle from its current position into the preplanned emergency mission.

Sensor management functions include cueing sensors based on static (part of initial mission data) or dynamic target information (target/change detection). Target information stored as part of the mission data and new target information stored as updates to the fact list (from onboard target/change recognition software or communications from the ground control) will trigger sensor management rules resulting in updated sensor commands (i.e. camera selection, field of view, zoom factor, pointing angles, etc.). The status of sensors can be monitored via messages, and compensating behaviors identified for any sensor related failures. Since the architecture supports direct subsystem communications, a mode would be available (which could be enabled/disabled by the sensor management software) to provide direct cueing between sensors. For example, the optical sensor and associated image processing software could indicate that an image has changed from a previous image or that a target has been identified. This would then prompt that sensor to send the target/area location over the local network to cue other active sensors. Another key aspect of sensor management is controlling the data being sent over the datalink to the ground control station. There are many factors which would influence this decision such as datalink availability (i.e. LOS vs SATCOM), environmental parameters (clouds, rain, light), image quality, target location, and previously sent data. These

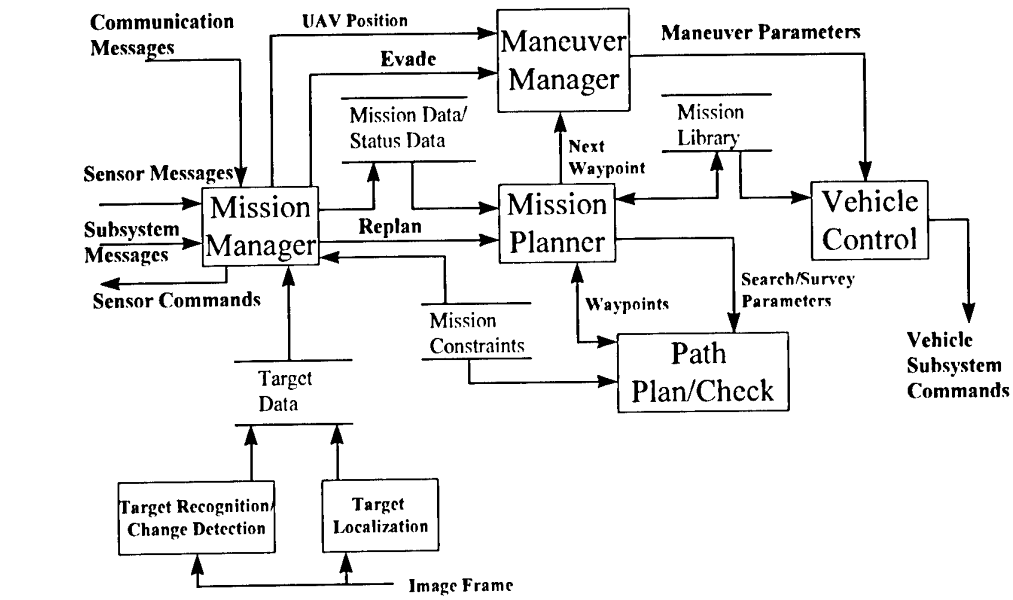


Figure 4 Software Architecture

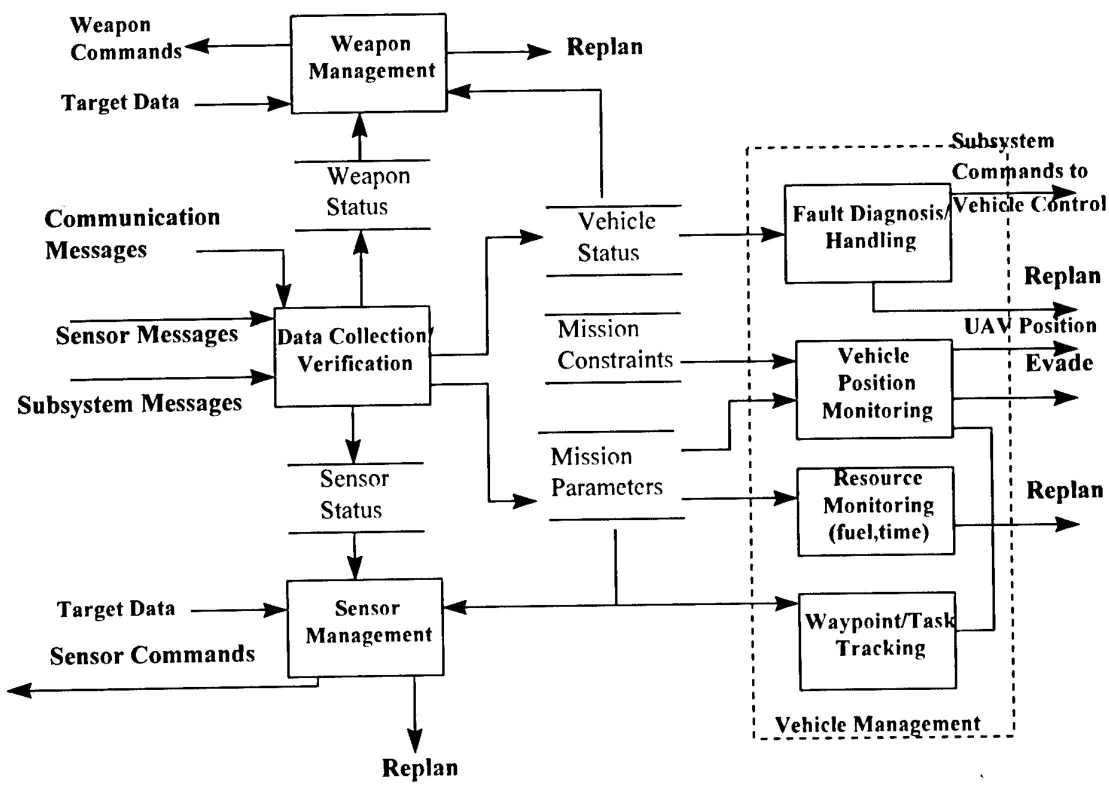


Figure 5 Mission Manager

parameters are similar to those used to decide which camera(s) should be active.

Vehicle management functions include fault diagnosis/handling, vehicle position monitoring, resource monitoring and waypoint/task tracking. Fault diagnosis and fault handling (recommendation of fault compensating behaviors to the vehicle control software) are vehicle dependent functions based on the vehicle configuration (i.e., subsystem redundancy, mission critical functions, emergency recovery actions, etc.). Vehicle management also includes the monitoring of the vehicle resources. Both fuel and time usage need to be monitored and compared to expected values to complete the mission. Any discrepancies which would impact the ability to complete the mission with sufficient reserves would trigger a mission replan (potential replans would include dropping lower priority waypoints/targets). For vehicle position monitoring, the current position compared to airspace constraints, mission constraints, terrain restrictions, and any known air traffic corridors provides indication of required actions. Any vehicle movement into restricted areas would result in an evade indicator which would prompt immediate action by maneuver planning software to position the vehicle back in the desired corridor to the next waypoint.

Monitoring of the mission progress is required to verify that the mission is proceeding according to plan. This function would include the monitoring of waypoint completion (based on vehicle position) including all characteristics and tasks typically linked to the waypoint definition (i.e., altitude, loiter pattern/area, communication tasks, payload configuration, etc.). The current mission definition compared to status information received from the vehicle subsystem and sensors provides an indicator of mission progress.

In order to have a consistent set of facts to support the reasoning process, messages need to be collected, combined and verified. The architecture provides message passing from the subsystems/ sensors directly to the application level software. An existing message passing protocol supports the collection of messages by each processor into message queues which are accessed by specific applications. One application is required to bring in the subsystem data for maintaining the dynamic set of facts on which reasoning functions are based. This data collection/verification utility is required for the collection of data into a single consistent set of facts to support the reasoning functions. This utility could be customized for the management software and vehicle specific requirements or could be applied solely against a database of formats and ranges with data output to defined tables. Specific data consolidation functions can be established as messages and processing of data are defined.

4. SUMMARY

This paper provides a description of communication utilities implemented to support fault tolerant features for a layered processor architecture. The defined software modules used existing message passing software based on TCP/IP, UDP protocols. The prototype software was tested to verify the routing, network diagnosis, and network recovery functions. Message traffic was monitored and after inducing a failure, the application was restarted without loss of state. The capability provided by these software modules can be readily applied with the definition of application specific messages and state variables.

The layered processor architecture and associated communication utilities were developed to provide a basis for improved autonomous vehicle performance. It supports this goal by providing graceful degradation due to processor failures, optimization of onboard processing capability, subsystem communications, data collection and validation of subsystem data to support context-sensitive reasoning, elimination of single point failures in the processor and communications architecture, and isolation of high-level processing functions from payload integration specifics.

A candidate software architecture for lethal UAV reasoning functions has been provided to establish the benefits of an integrated design approach. This software architecture supports all key reasoning functions including; sensor management, weapon management, vehicle control, fault handling, target identification, target localization, maneuver control and mission replanning. The indicated data flows in the figures provided identify interaction between these functions and subsystems. The defined software architecture for lethal UAV application builds on the layered processor architecture's key features to enhance the vehicle's mission effectiveness and survivability.

5. REFERENCES

(1) Hess, D.K. Safford, D.R., Pooch, U.W., and Williams, G.N., "FTMP: A Protocol for Distributed Fault Tolerant Operating System Services", *in* "Proceedings of the 1992 Symposium on Autonomous Underwater Vehicle Technology", 1992.

(2) "LonTalk Protocol", LonWorks Engineering Bulletin, Echelon Corporation, April 1993.

(3) "LonWorks Self-Healing Ring Architecture", LonWorks Engineering Bulletin, Echelon Corporation, January 1995.

(4) "Parallel I/O Interface to the Neuron Chip", LonWorks Engineering Bulletin, Echelon Corporation, January 1995

Image Data Management for Tactical Unmanned Airborne Surveillance

Michael R. Davenport
email: mrd@mda.ca

Hans Wehn
email: hw@mda.ca

Ian Burke
email: burke@mda.ca

MacDonald Dettwiler and Associates
13800 Commerce Parkway
Richmond, B.C., Canada, V6V 2J3

1 SUMMARY

This paper examines how *more* information and *better* information can be extracted from UAV data streams, and how that information can be presented to operators in the most effective manner possible. It examines the role of data management in all three phases of tactical reconnaissance: mission planning, mission execution, and post-mission analysis. It then describes some newly-developed tools for precisely positioning each pixel, fusing multiple images, extracting new information, and providing an accessible archive of that information. When implemented successfully, such a data management system can substantially increase the operational value of existing UAVs.

2 INTRODUCTION

A number of NATO forces are developing Unmanned Aerial Vehicles (UAVs) for Reconnaissance, Surveillance, Target Acquisition and Battle Damage Assessment missions. The UAVs can be used in both battlefield and peacekeeping situations to provide critical information about over-the-hill or over-the-horizon enemy activities. Tactical UAVs will form an important part of future NATO equipment, largely because they are "characterized by affordability, effectiveness, efficiency, versatility, and unity of effort" [9].

As UAV technology matures, however, attention is shifting from the shear problem of acquiring the data (e.g. avionics, controls and communications) to look at ways of optimizing the value of the data that has been collected. This is a high-leverage activity — it is not difficult to imagine how software systems could double the value of UAV information at very little operational cost, simply by smart data management.

2.1 Challenges of UAV Data Management

Some of the specific challenges associated with data management of UAV data streams are:

- **limited context:** payload operators often have very limited context information (e.g. no peripheral vision) about the incoming image stream;
- **high volumes:** video or SAR data streams, integrated over the duration of an extended mission, become very high volumes of archived data.
- **varying conditions:** the ground-resolution, viewing angle and lighting conditions of UAV images vary widely from mission to mission, and even within one mission, presenting obstacles for automated information extraction and data fusion algorithms;
- **real-time requirements:** some tactical situations demand real-time data management, but the amount of real-time support is limited by current computational power.

UAV systems with "baseline" capability deliver a real-time view of the incoming data but provide little or no data management capabilities. The current research focuses on developing new tools to link the Payload and UAV operators with archives of previous and peripheral information, as shown in Figure 1.

2.2 Research Context

The research and development reported here was done in a number of contexts, some that are specifically for UAVs, and others that are for airborne and spaceborne data. MacDonald Dettwiler is working with Bombardier, for example, in the

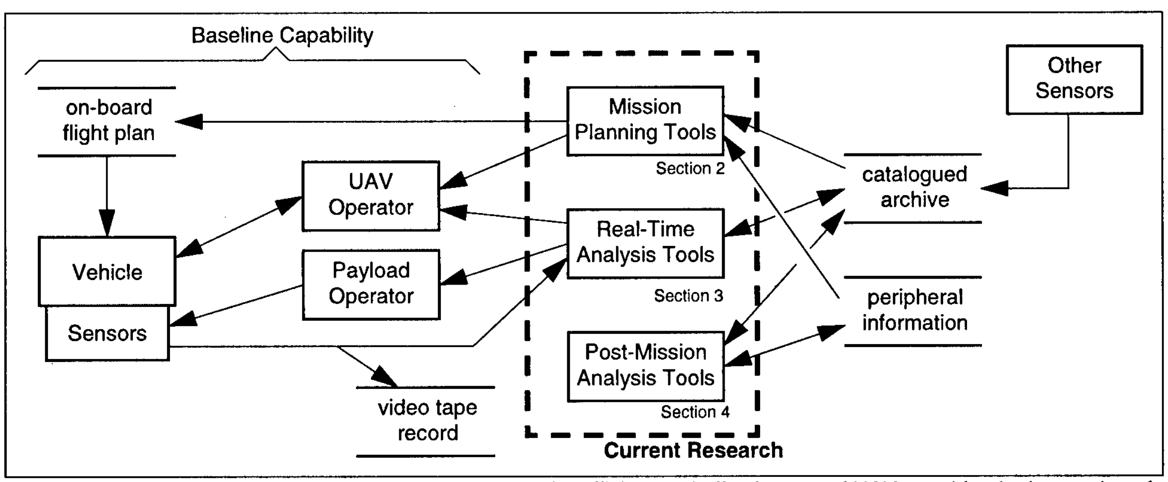


Figure 1: Good management of image data is essential for efficient and effective use of UAVs, and for the integration of UAV data into larger systems in support of operational requirements. The current research has developed tools to generate indexed archives of images and peripheral information, and to use those archives for Mission Planning, Real-Time Analysis of the Data, and Post-Mission Analysis of the Data.

Paper presented at the AGARD MSP Symposium on "System Design Considerations for Unmanned Tactical Aircraft (UTA)", held in Athens, Greece, 7-9 October 1997, and published in CP-594.

development of data management capabilities for their UAV programs. That work includes the development of a Baseline Ground Control Station for the CL-327 Vertical Takeoff and Landing (VTOL) UAV [12].

Data Fusion research, including the development of the Hyperlens (Section 4.5) and the web browser (Section 5.4), was done by MacDonald Dettwiler in cooperation with Canadian defense laboratories in Ottawa and Valcartier and with the joint Directorate of Imagery Exploitation. Change detection (Section 5.2), radiometric calibration (Section 4.3), geocoding (Section 4.1) and mosaicking (Section 4.4) were developed under contract to the US Government Spectral Information Technology Applications Center (SITAC), formerly DLPO [13].

All of these research initiatives shared the common goals of increasing the operational value of remotely sensed imagery and maximizing the effectiveness of the human operators. This is done by: removing from them all the repetitive tasks that computers do very well and providing them with intuitive and efficient tools for doing the tasks that only humans can do well

3 MISSION PLANNING AND PREPARATION

Research is being done to give UAV Mission Planners improved access to images and related information that they can use to make more informed route plans and target designations. Maps will still be the most important planning aids but they will be supplemented by:

- archival imagery (e.g from satellites);
- data from previous flights;
- annotations by previous mission planners; and
- hyperlinks to associated information pages.

The intention here is to give Planners the option of superimposing background images or icons onto the base maps, thereby allowing them to, for example:

- find locations where the maps are out of date by comparing them to low-cost commercial satellite images, as illustrated in Figure 2;
- review the previous UAV coverage to determine gaps in the data and locations where information is outdated;
- arrange for a new mission to view a site at the same angle as a previous mission, so that the two views can be more easily analysed using automated change detection algorithms;
- click on an icon to bring up a page of notes written by previous analysts or planners, using hyperlink technology described in Section 5.4.

The purpose of the new tools is to help Mission Planners make better decisions about targets, view angles, and transit routes for the vehicles. Planners that are newly assigned to a zone can benefit from their predecessors experience by reading their annotations and noting previous missions. Plans can then be made not only within the geographical and tactical context, but also within the context of previous missions. Ultimately, this will result in better allocation of resources — the UAVs will go where they are needed most.

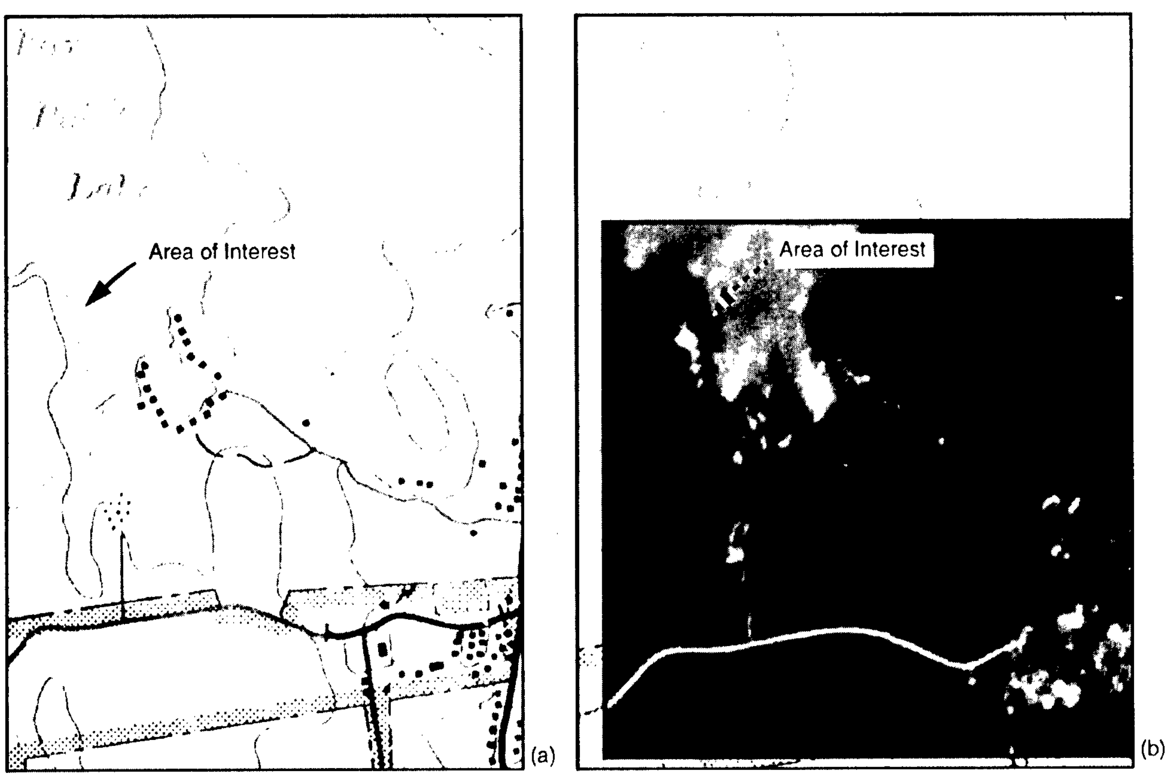


Figure 2: New tools can help Mission Planners by using archival data to reveal places where maps are out of date, or where recent changes have been made. In this example, a SPOT image (b) reveals new developments along a lake shore that are not shown on the map (a). Mission Planners might choose to investigate further by routing a UAV over the site. The tool being used here is a "Hyperlens", as described in Section 4.5.2.

4 CONTEXTUALIZATION OF REAL-TIME DATA

One challenge in operating UAVs is the lack of context information easily accessible to the payload and vehicle operators. The payload operator, for example, is looking "through a soda straw", with no peripheral vision, at what may be a very small patch of ground. Context is usually gained by zooming back to the context of a wide-angle view, and then zooming in again to see details. Context and details are usually not accessible at the same time.

A number of tools have been developed to help place incoming information into context:

- geocoding & geocorrection tools that incorporate UAV dynamical models (Section 4.1)
- coregistration tools for optical and SAR data (Section 4.2)
- an automated mosaicking tool (Section 4.4)
- a radiometric calibration tool (Section 4.3)
- tools for simultaneous viewing of images (Section 4.5)

4.1 Geocoding & Geocorrection

The first step in putting incoming information in context is to calculate, as exactly as possible, where the information came from. Geocoding is the process of finding the location of each image pixel on the surface of the earth [15]. Geocorrection is the resampling of an image to a known map grid.

The success of the geocoding process entirely depends on the quality of available information about the UAV and the sensor. The most sophisticated geocoding algorithms use data and parameters such as the following:

- UAV motion telemetry: time, GPS location, roll, pitch, yaw, and heading;
- payload instrumentation: azimuth, elevation, and zoom of the camera;
- dynamic properties of the UAV: moments of inertia, airspeed, control surfaces, and natural frequencies;

These values are incorporated into a Kalman filter to estimate, at each moment, the exact location and orientation of the UAV and its sensors. The Kalman filter uses a rigorous model of the UAV trajectory, payload dynamics, and instrumentation noise to estimate the sensor motion, based on incomplete or inconsistent information from the UAV telemetry, as sketched in Figure 2. Information taken from different sources is properly weighted so that the estimates are statistically accurate .

Geocoding to accuracies of a few pixels or less usually requires ground control points (GCPs). Each GCP provides a precise and reliable alignment between the incoming image data and a map or latitude/longitude grid. Once a few GCPs have been established, Kalman filters can interpolate the motion of the sensors between them. When GCPs are not available, such as for UAV flights over water, the absolute error in the geocoding will only be as good as the accumulated errors in all the telemetry data.

GCPs may be manually entered or automatically estimated. The Payload Operator, for example, may note a road intersection in the video data and identify it with an intersection that is marked on the map, thus establishing a tie point. In some cases, incoming imagery can be automatically coregistered to archived imagery or maps, using the algorithms discussed in Section 4.2. When that is possible, the geocoding process can achieve the best possible accuracy, without requiring regular operator intervention.

4.2 Coregistration

The geocoding and geocorrection tool cannot, in most cases, find the location of each pixel in an image to sub-pixel accuracy. This means that when two geocoded images are spliced together, or viewed simultaneously, they will seldom match. There are a number of applications, such as change detection and mosaicking, where this would be a problem. The problem can be avoided by coregistering the two images to subpixel accuracy and thus achieving relative positional accuracy that is much better than the absolute accuracy.

4.2.1 Coregistering Optical Images

A new fully-automated coregistration tool for coregistering two optical images has recently been developed and tested, and is now in use by a number of customer agencies [14]. The high level of automation of the tool makes it particularly useful for large data streams where manual tie point extraction would be unacceptably expensive. An excellent example of such a data stream is the video signal from a UAV.

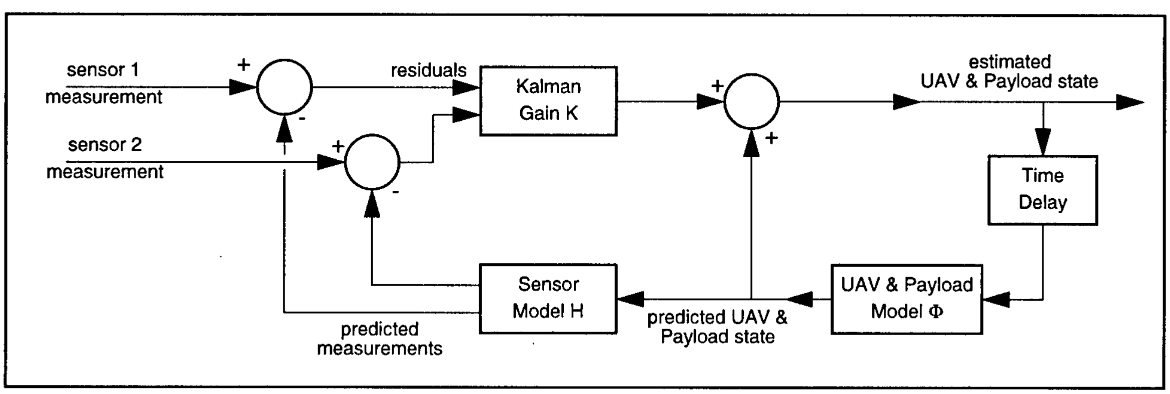


Figure 3: Precision geocoding of UAV data is based on a Kalman filter that incorporates a detailed model of the aircraft trajectory and dynamics, and the Payload motion. This simplified block diagram shows how the Kalman filter modifies its estimate of the state of the UAV and the Payload in order to best explain the measurements reported by all the sensors. Much of the challenge of geocoding lies in designing appropriate sensor and UAV models and Kalman gain.

The automated algorithm used by the new tool can be summarized as follows:

1. it is assumed that the images have been geocoded to establish a best estimate of the pixel locations, and that the two images have been found to overlap;
2. small patches (10x10 up to 30x30) are selected from the overlapped zone in one image and moved around the matching zone in the second image;
3. the correlation between the images is calculated at each shifted location, for each patch;
4. the shape of the correlation surface is analysed. Surfaces with low peaks, multiple peaks, or with spatial anisotropies are rejected;
5. the correlation is re-calculated at progressively finer scales, to avoid ambiguities and speed up the search;
6. once a set of candidate tie points have been extracted, a Kalman filter is used to determine whether the selected tie points make sense from the point of view of sensor and UAV dynamics. Tie points that do not make sense are rejected.

4.2.2 *Coregistering Optical and SAR Images*

Coregistration of SAR and optical data is somewhat more difficult than coregistering optical data with other optical data. One problem is the very different radiometrics of the two types of image: an object that is darker in an optical image may be darker or lighter in a SAR image. That problem, together with the large amounts of speckle in most SAR images, means that the images cannot be correlated in the standard way.

An alternative approach has been developed which is similar to that in 4.2.1, but uses a very different statistical measure to find the correlation peak [7][8]. Steps 2 and 3 are replaced with:

2. construct templates that have the same shape as high-contrast shapes in the optical image and move the template around in the SAR image, as shown in Figure 4;
3. calculate, at each point, a statistical estimate of the homogeneity of the SAR image inside and outside the template, as described in [7], and use that as a measure of the correlation;

Work remains to be done in automatically extracting templates from the optical images, so this tool is not yet fully automated

4.3 Radiometric Calibration

Visual imagery is often partially obscured or discolored by atmospheric effects such as haze, smoke, absorbtion, or back-scattering. The goal of radiometric calibration algorithms is to modify the color of an image so that it looks, as much as possible, as it would if the sensor was ideal and there was no air between the landscape and the sensor. This cannot, in general, be achieved precisely unless radiometric control points (places on the ground with well-known spectra) are available.

A semi-automated radiometric calibration tool has been developed that significantly improves the spectral quality of UAV video images. The tool works as follows:

1. an operator identifies three or four known land-cover types in the video stream, such as grass, asphalt, or concrete;
2. the tool compares these samples with a library of known spectra and calculates an optimal affine transform for the spectral bands so that the modified spectra match the exemplars. This process corrects for both atmospheric and sensor calibration errors at the same time;
3. the affine transform is then applied to all pixels in the current frame;
4. a radiometric tie-point is established in a small window around each geometric tie point and is used to transfer the information between overlapping frames. As a result, the correction propagates along the image sequence from the frame that holds the exemplars.

This method is inexact insofar as it relies on the operator finding pixels on the ground that closely correspond to the exemplars in the spectral library, when the operator has no way of confirming

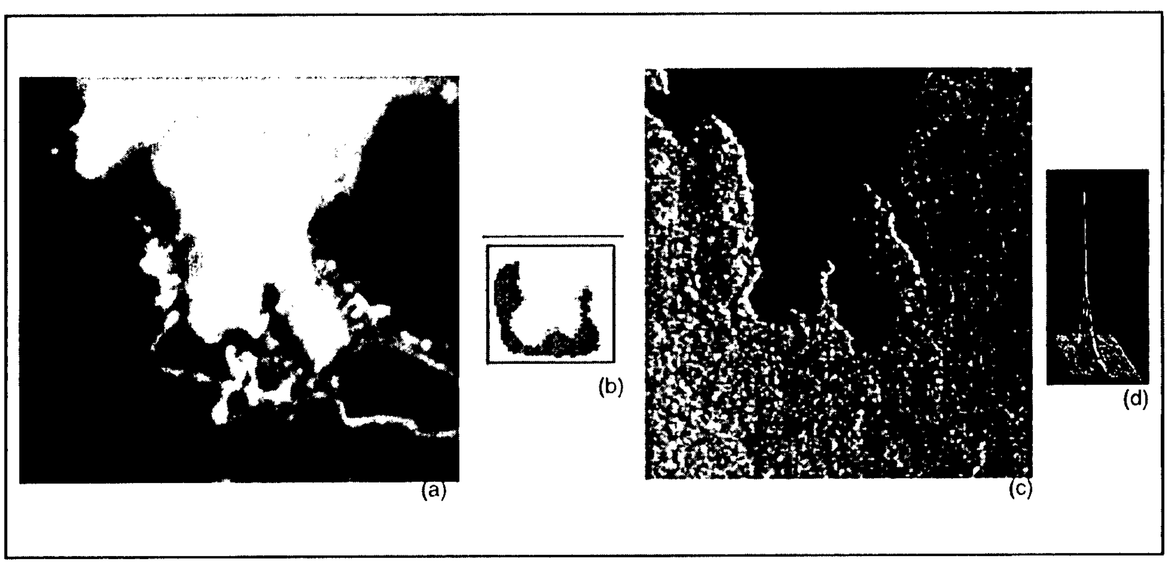


Figure 4: When coregistering a SAR image to an optical image, standard correlation calculations fail. A new method has been developed in which a template (b) is extracted from the optical image(a), and then moved around the SAR image (c). At each point, the speckle statistics inside the template are compared to those outside and those on the boundary, to generate a statistical estimate of the match at each point (d).

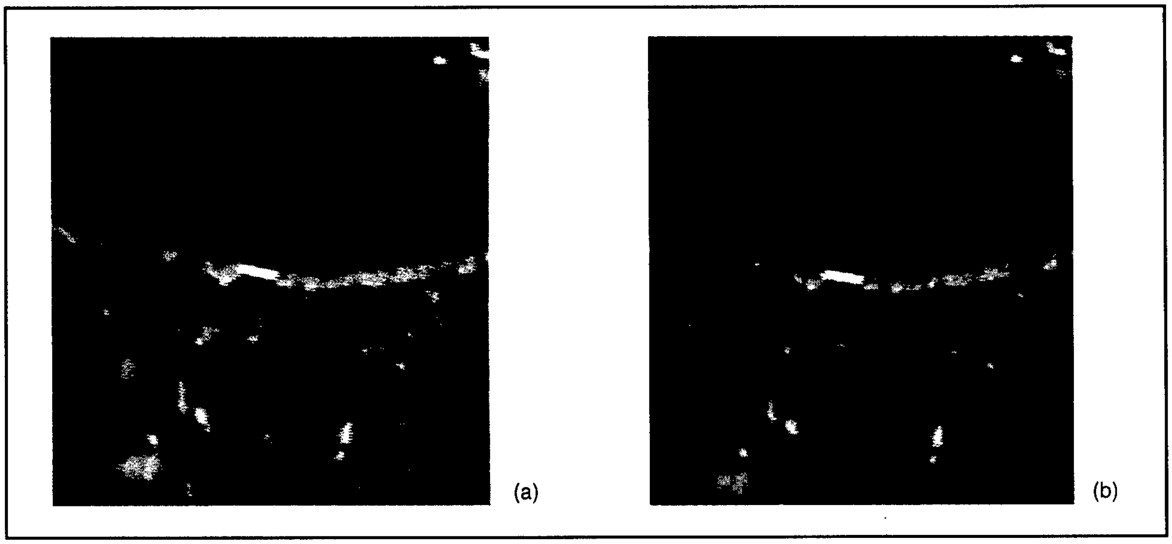


Figure 5: A radiometric calibration tool has been developed that corrects spectral errors caused by atmospheric scattering or absorbtion, as well as by sensor or processing errors. The operator finds pixels of known identity in the source image (a), and the algorithm modifies the spectrum in (b) to match spectral library entries for those substances.

the identity of the ground pixels. In practice, however, the method produces images with spectra that are significantly more correct than the source images and it has the advantage of working, if necessary, when no radiometric control points are available. Figure 2 illustrates how the clarity of an image can be improved by this form of atmospheric correction.

4.4 Mosaicking Sequential Images

Viewers are helped in the interpretation of video image sequences by the way that each frame exists in the context of surrounding frames. When a single frame is extracted, however, much of the context is lost. Mosaicking combines a sequence of images so that all the context information is visible in a single (larger) image. This also has the advantage of removing redundant information because only one version of the overlapping parts of the scene are presented.

A fully-automated tool has been developed [15] for mosaicking image sequences such as those transmitted by UAVs. Figure 2 shows a mosaic produced from Predator UAV video data [1] by the tool. The tool works in the following way:

1. it finds geometric tie points where the frames overlap, using the coregistration tool described in 4.2.1;
2. the operator identifies a set of known materials in the first patch, and the software creates a set of radiometric control points for absolute calibration;
3. it resamples the newly-added frame to the grid of the pre-integrated frame, using the geometric tie points;
4. it uses a least-squares algorithm to select a spectral correction that matches the spectra at identified "radiometric tie points" in the overlapping region.
5. if necessary, it applies a spectral "correction kernel" to every frame to accommodate spatial variations in brightness (due, for example, to systematic variations in the bidirectional reflection distribution function or "brdf").

A similar mosaicking capability has been demonstrated by the Sarnoff labs using data from an Unmanned Ground Vehicle [4].

4.5 Co-Display

Mosaicking doesn't work for images that have significantly different content. It would not be useful, for example, to form a mosaic using a topographic map, a video image frame, and a SAR image, because the information in the overlap areas is complementary rather than redundant. Yet there is clear value in viewing a SAR image in the context of an underlying map.

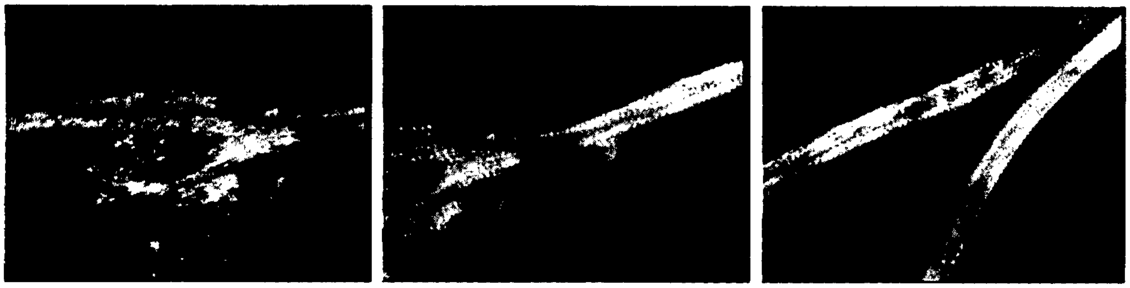
One solution is to *co-display* the images, so that they maintain their individual identities while being viewed in context. Two approaches to co-displaying were prototyped and evaluated, as discussed below.

4.5.1 Co-Moving Cursors

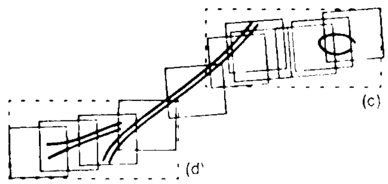
The co-moving cursor approach displays two or more images side by side with co-moving cursors under the operator's control. If a SAR image and a video sequence are co-displayed in this way, for example, then the operator can point to a feature in the SAR image, and look on the video to find the corresponding point. The SAR image is thus being interpreted in the context of the video image.

Figure 7 shows an example use of co-moving cursors in a change detection application. The two lower windows show the two source images with detected changes overlaid. The small upper windows show details of the cursor vicinity. The operator can use the co-moving cursors to relate features in the source images to each other, and to the detailed views. In this example, the images have all been coregistered and resampled to a common grid.

Co-moving cursors can also be used for sets of images that have very different projections. Consider the example of two images of a common scene, in which one view is from nadir and the other is oblique. In order to coordinate the cursors, a homeomorphism must be established between the two scenes. Generally this will take the form of look-up tables that are the same size as the images and that are derived from a digital elevation model and view-angle parameters.

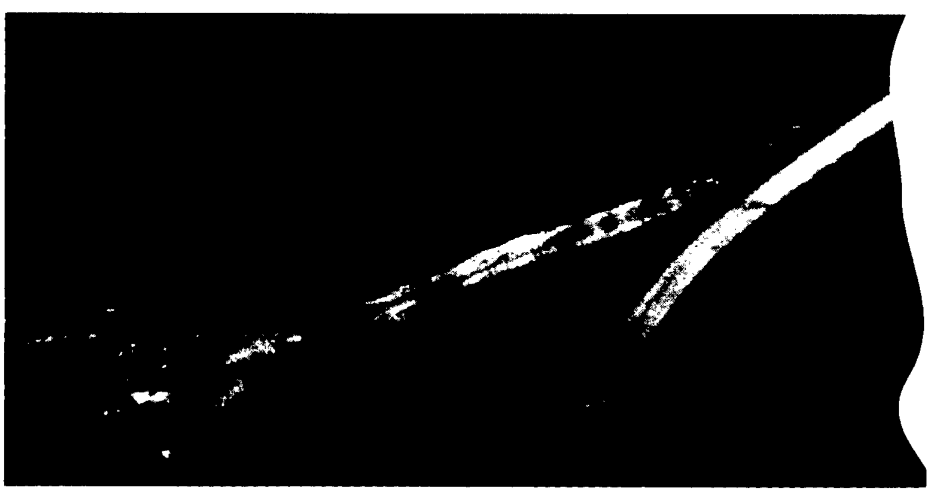


(a) Example frames from the original video sequence



(b) Sketch of the frame locations and mosaic sub-sections

(c)



(d) two sub-sections of the final mosaicked scene

Figure 6: Video frames are normally viewed as a time sequence, so that each frame in understood in the context of previous and subsequent frames. To provide the same context for a static image, an automated tool has been developed that mosaicks the frames together. This example is from a video sequence showing dug-in armour that was acquired by the Predator UAV in Bosnia in 1995 [1]

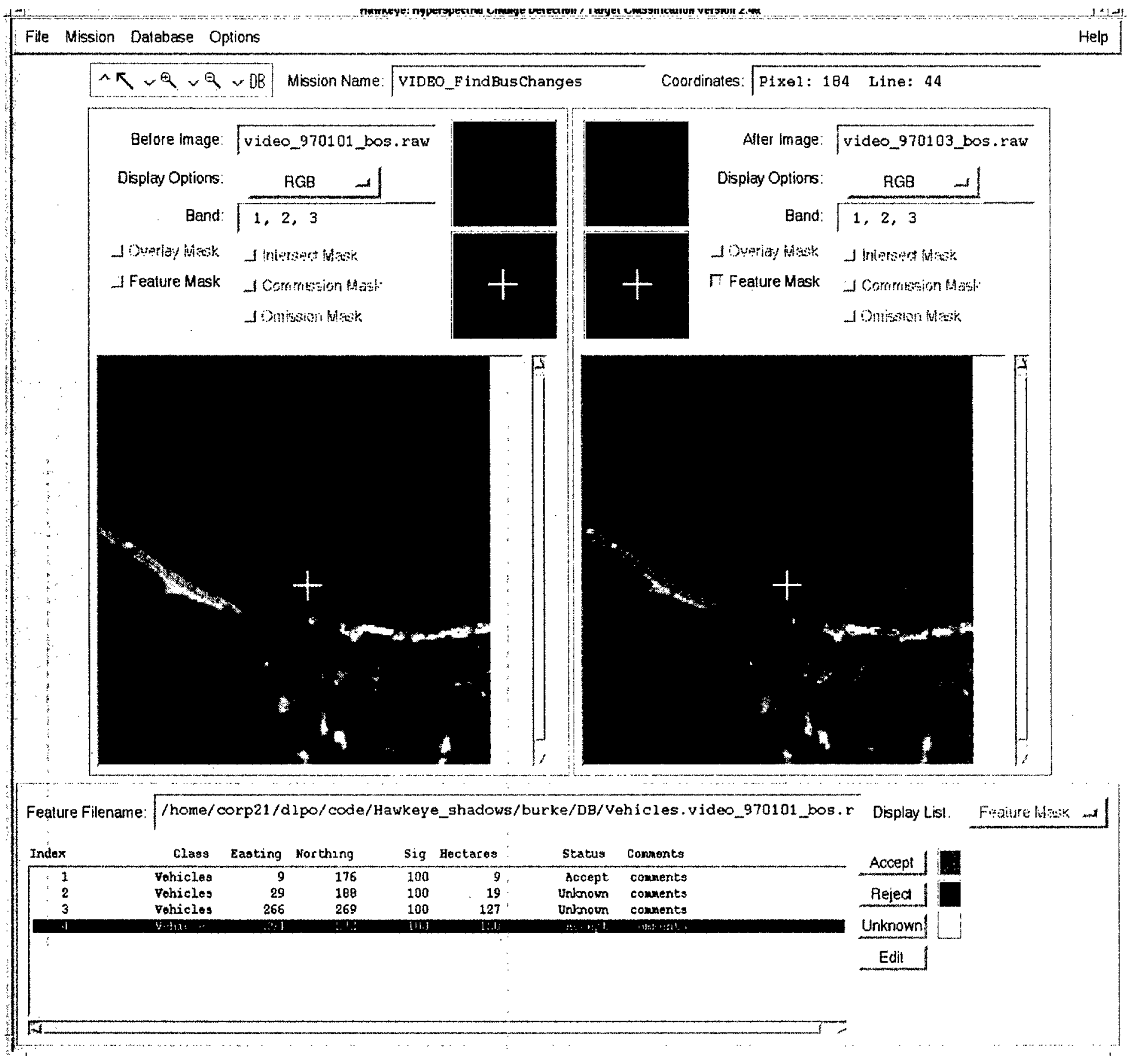


Figure 7: One example of co-moving cursors is the "Hawkeye" change detection application. The two large windows show the same scene, taken at different times, with close-ups shown in the small windows. The operator can move all four cursors together to get before and after information about a specific pixel. The co-moving cursors are one method for interpreting each image in the context of the other image. These video frames were taken in Bosnia by the Predator UAV [1].

4.5.2 Hyperlenses

Another method for co-viewing two images is to use a "hyperlens", which is a square window overlaid onto an image, through which a different image can be seen, precisely coregistered to the foreground image. An operator can move or resize each hyperlens in real time to see different parts of the underlying image. The two images remain coregistered at all times. Hyperlenses are based on "Magic Lenses" developed at Xerox Park [2].

The real power of hyperlenses stems from their dynamic nature, so their behaviour cannot be fully illustrated by static images. In Figure 8, for example, a hyperlens is shown in two positions, both on and off a target. When the hyperlens is off the target, the target is invisible behind camouflage. When the hyperlens is moved over the target, it shows up as a bright spot in the underlying SAR image. An analyst would correctly interpret this as a possible armoured vehicle, because of the camouflage and proximity to a road. Neither the SAR image alone nor the video image alone would be as convincing.

Experience shows that operators typically move the hyperlenses back and forth across an area of interest so that their eyes' can use optical persistence to view both images at the same time. This is similar to the way that analysts co-view paper image products by flipping one image on and off another.

Masks are used in conjunction with the hyperlenses so that regions appear transparent where no information is available. This makes it possible, for example, to overlay icons or graphics onto the base image, inside each hyperlens.

The biggest technical challenge in developing Hyperlenses for client-server (Sun) architectures was to achieve instant and smooth updates of the lenses as they move. Data links are not fast enough on client-server machines for the central server to control the window updates, so it was necessary to first download all the images into X-Term memory, and then use a local process to control the hyperlens window. Once the solution was proven, this was implemented as an X-Windows widget, and will soon be re-implemented as a JAVA applet.

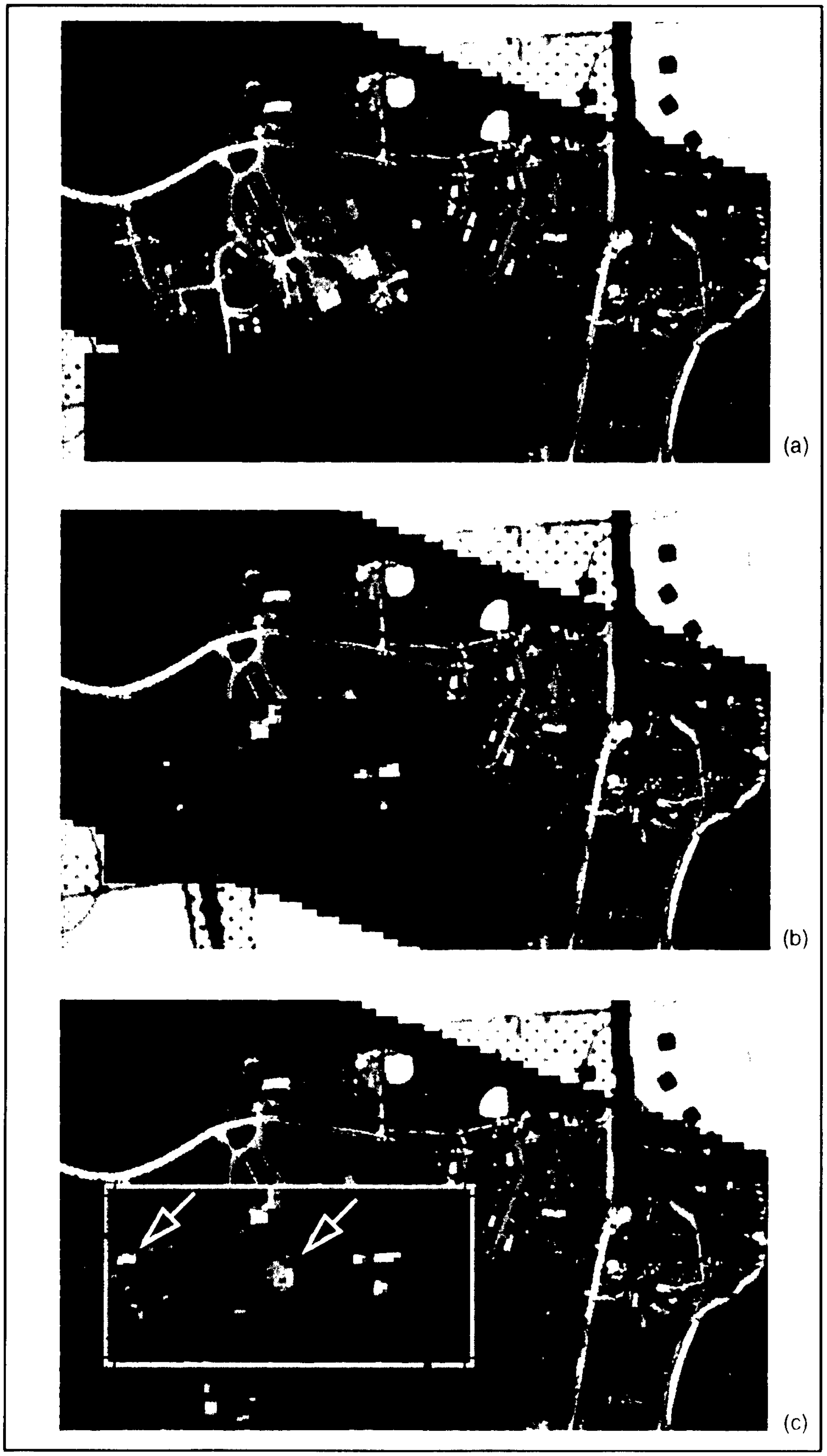


Figure 8: Hyperlenses are an effective tool for viewing dissimilar images and maps in context. In (a), (b) and (c), an optical image, overlaid onto a topographic map, remains unchanged. Pixels that have no optical data show the underlying mapsheet. In (a) and (b), a hyperlens is moved up over the optical image to show a coregistered Synthetic Aperture Radar (SAR) image. In (c), a second hyperlens, showing a SAR scene taken on a later day, has been added revealing two suspicious targets not previously present, as indicated.

5 DETAILED POST-ANALYSIS OF IMAGES

Although some automated image analysis functions are currently too computationally intensive to be done in real-time, they can still deliver valuable insights about a region of interest, in near real-time, to a tactical reconnaissance unit. Of particular interest are:

- algorithms that can automatically scan large amounts of data looking for specific features. Target detection and change detection algorithms are examples of these, as discussed in Sections 5.1 and 5.2; and
- processes that can be applied to selected scenes or sequences of scenes to extract as much information as possible. Super-resolution is an example of such a process, as discussed in Section 5.3.

As large amounts of information are collected and extracted, it becomes increasingly difficult to find the information that is needed in the growing archives. Section 5.4 describes some prototype solutions that have been investigated, using Web-like user interfaces and hypertext links.

5.1 Automated Target Detection

A great deal of research has been devoted to the development of automated target detection systems for virtually every type of imagery. As a result, many very successful algorithms are available, although they tend to be quite sensitive to variations in image quality. The human eye remains the most robust target detector, although for certain data sets it can be outperformed by automated algorithms.

For tactical surveillance, automated target detection algorithms can supplement the work of trained operators, particularly when large amounts of data need to be scanned. If a blue car is seen by a UAV in a suspicious location, for example, an operator might use an automated target detector to search previously-recorded imagery for other possible sightings of the same car. To search the same data by hand would be prohibitively expensive — taking roughly as long as the original UAV missions.

Currently-available detection engines are able to search on criteria such as spectra, size, shape, speed, and context (e.g. proximity to roads). Even so, searches will in general "find" a number of false targets, and the resulting detections will need to be reviewed by a human operator. The target detection engine does not replace the operator, but rather reduces the search space to a size that the operator can effectively search.

It is important that target detection tools do not just highlight the targets, but also automatically create a record suitable for storage in a geographic information system (GIS). The target records should include:

- location (time and map coordinates) of the target;
- size and shape of the target; and
- an image chip of the target.

This allows an operator to quickly scan the candidate targets, and confirm or discard each one. The Change Detection engine described in Section 5.2, and shown in Figure 7 can be configured as a target detector, and customized for a variety of missions and sensors. Experience with SITAC confirms the efficiency of being able to rapidly scroll through a list of detections, confirming or rejecting each candidate with the press of a single button.

5.2 Change Detection

Change detection is important to tactical commanders for the following reasons:

- most activities that are of tactical interest, such as force movements or equipment installations, will show up as changes on the ground;
- the Recognized Tactical Picture (RTP) for an area of interest (AOI) can be kept current by detecting changes and then making incremental changes. This is much less costly that doing complete re-assessments of the AOI; and
- automated change detection promises to be more technically achievable than target detection.

For these reasons, strategic and tactical intelligence units have given change detection research a high priority.

The "Hawkeye" change detection software, shown schematically in Figure 9, was originally developed under contract to the Defense Landsat Program Office [6]. It is currently used by SITAC to analyse remotely sensed imagery for the US Government, and it is being integrated into the British Columbia Ministry of Forests as a forestry management and monitoring tool.

The success of the Hawkeye software is due largely to its use of mission-specific algorithms to differentiate between "significant" and "nuisance" changes. The significance of a change is, of course, highly situation-dependent. Changes that are a nuisance for many missions include:

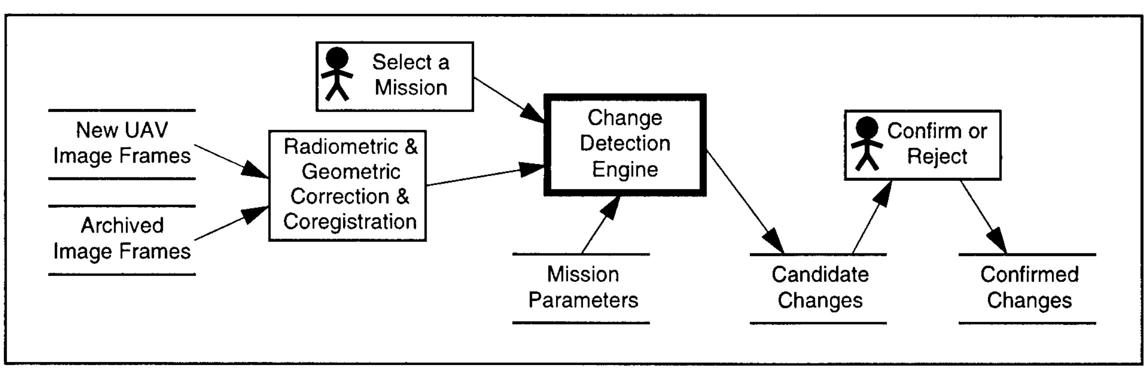


Figure 9: The "Hawkeye" change detection system relies on user-definable "missions", because the significance of a change is determined by the goals of the operator. Hawkeye extracts candidate changes from the imagery and stores them as records in a GIS. The operator can then review the changes, using the user interface shown in Figure 7.

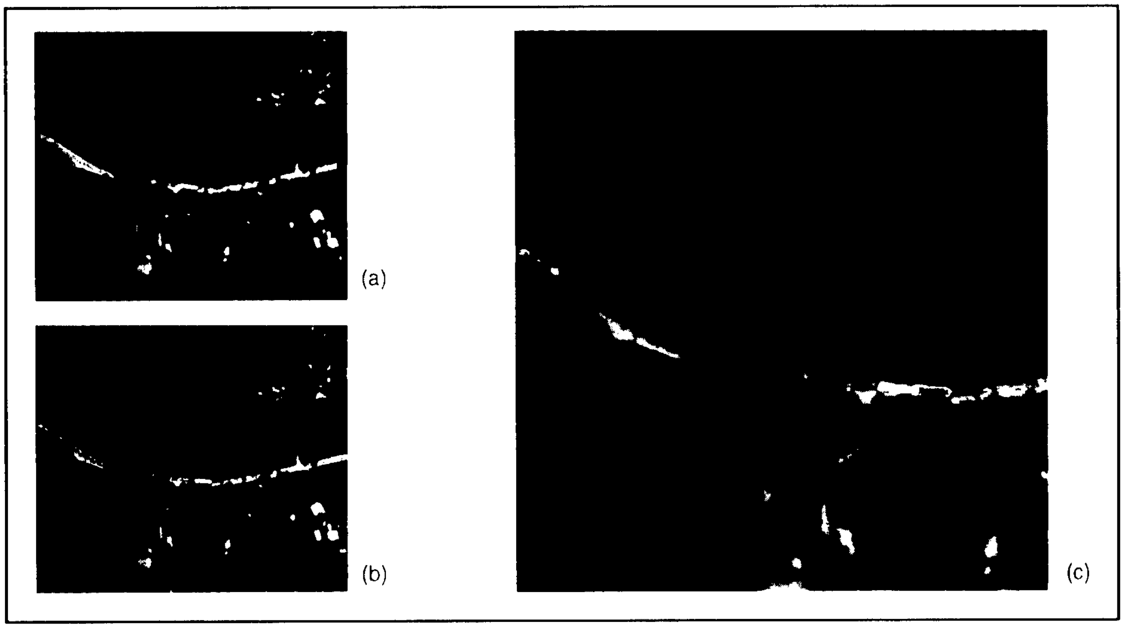


Figure 10: An automated Change Detection tool can highlight changes or motion that an operator misses. In this example, a bus and a car are visible moving along a rural road in the video image, as shown in (a) and (b). The camera in this example pans through the scene very quickly, and most viewers only notice the bus. The automated algorithm is not distracted, however, and correctly highlights the car moving in the opposite direction. In (c), yellow and green masks are used to mark the before and after locations of the vehicles.

- pixel-shifts due to movement of the camera
- changes due to variations in the viewing angle
- changes in illumination
- atmospheric or weather changes (e.g. clouds)
- seasonal changes (e.g. snow cover)

Changes that may be significant for tactical missions include:

- bomb damage
- newly-installed weapons
- tracks left by mobile equipment
- cutting of trees and clearing of land.

Motion detection is a change detection where the "before" and "after" images are from a single time sequence, such as a video. Motion detection missions are distracted by only two types of nuisance change: pixel-shifts and viewing angle changes, and are generally able to extract both location and speed of targets.

Figure 10 shows an example vehicle motion-detection mission using Predator data. The mission algorithm examined two temporally-close frames of the video, and looked for spectral changes with sizes corresponding to vehicles. Interestingly, the algorithm found a small car that was initially missed by the human operators, whose attention was distracted by the movement of the larger bus. False detections occurred in parts of the image not reproduced here, due to changes in sun glint on roofs of buildings.

Change detection between different UAV sorties is more difficult than motion detection because the nuisance changes are much more severe. Howvere, the usefulness of such "multitemporal" change detection is correspondingly higher, so it remains a high priority.

Forethought during the planning process can be important to the success of multitemporal change detection missions. By flying the UAV on a second sortie along identical flight paths and at the same time of day, and by pointing the camera onto the target at the same time in the flight, nuisance changes due to viewing angle and illumination can be minimized. Automated tools such as those discussed in Section 3 can aid in this planning process.

5.3 Super-Resolution

Spatial resolution is critical in surveillance data because it determines the amount of information that a skilled analyst can extract from the data. Factors that limit the resolution of an image acquired by an electro-optical camera include:

- the resolution of the optics in the camera, and
- the size of the pixels in the camera's sensor (e.g. CCD array).

The former limit probably cannot be exceeded, but the latter can be stretched using "super resolution" methods.

Super-resolution algorithms extract information from a sequence of similar images to create a single image with higher resolution than any of the source images. The algorithms use the misalignment of pixel boundaries from one image to another, to extract sub-pixel details about the scene. Some algorithms do this by transferring all the low-resolution images to a single higher-resolution grid and then de-blurring using a deconvolution filter [3][10]. These algorithms have trouble with source images that are misaligned or at different scales. More recent research [5][11] use an iterative "back projection" algorithm that is more robust to image misalignments, motion, and changes of scale. For NTSC video, the two interlaced fields must be super-resolved as separate frames if there is any camera motion.

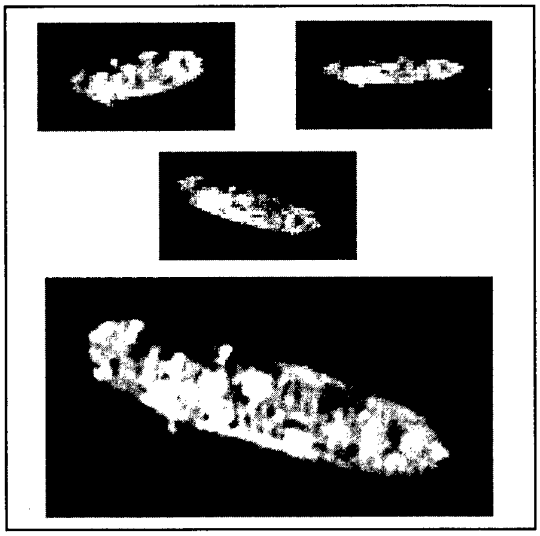


Figure 11: Super-resolution offers analysts a more detailed view of a target by fusing multiple source scenes, such as multiple frames from a UAV video signal. New research has demonstrated the feasibility of super-resolving images taken from different passes of an airborne sensor, as shown here. Data is from the Compact Airborne Spectrographic Imager (CASI).

UAV video sequences are the natural candidates for super-resolution because they give multiple views of the same scene, with different pixel alignments. The increase in the resolution will depend on many factors, including camera optics, electronic noise, and blurring due to motion of the camera.

Super-resolution can also be done between scenes taken at different times. These present additional challenges, however, in that the source images may be rotated, scaled, and stretched relative to each other. Research at MacDonald Dettwiler has addressed these problems using a back-projection algorithm that iteratively refines the affine transform that represents the mis-registration and distortion of the source images. Figure 11 shows the new method applied to a set of three source images spaced approximately one half hour apart.

5.4 Web-Structured Information Pages

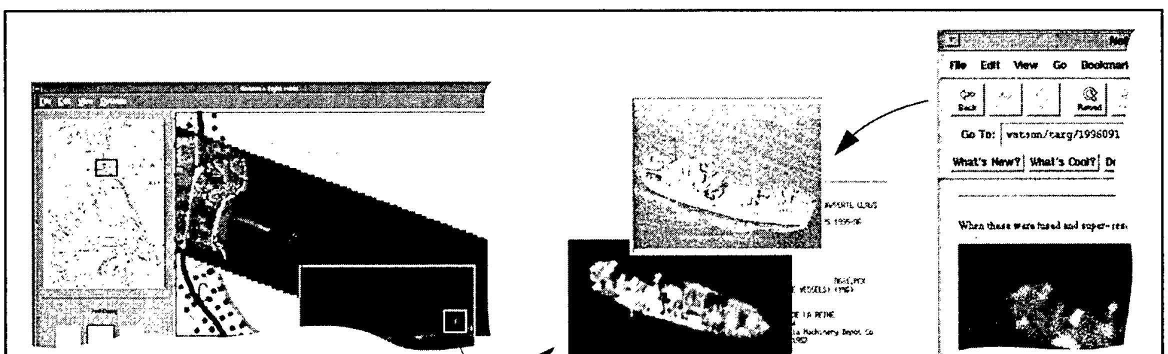
All of the above tools, together with commonly-available image analysis workstations and their associated tools, are designed to convert image *data* into *information*. A video image of a airstrip certainly has value, for example, but a map of the airstrip with facilities and aircraft located and identified has even more value. This introduces a new problem: as data is distilled into information, it becomes more abstract and may no longer be associated with a single geographic location. How can the information be made accessible to all potential users in a user-friendly way and at a reasonable cost in manpower?

A prototype information network based on World Wide Web technologies was tested. Users can access the information in this secure intra-network using a Web browser (such as Netscape) or using icons displayed on a map-based "Situation Picture", as sketched in Figure 12. Links to associated information are encoded in an extended form of hypertext markup language (html). They appear as highlighted text in the Web browser and as icons in the Situation Picture.

The key question being addressed by the prototype is "how can information best *advertise its existence* so that future analysts get maximum benefit from it?" Some of the lessons learned include:

- the operator must be able to select what classes of icon should be displayed on the Situation Picture. This includes being able to hide or delete information that is outdated or superceded;
- hyperlenses can be used to filter which icons are displayed. Thus, ship icons are thus only visible through a "detected ship" hyperlens. This approach works but was not noticeably superior to the more common menu-switch approach;
- automatic methods must be used to generate web pages for new targets as they are detected, and to amalgamate web sites when two targets are identified as the same or when new information is derived. Present manual methods are far too slow.

This move toward an html-based information network is consistent with a number of government and military initiatives, particularly in the United States.



(a) "Situation Picture" browser (b) Underlying information (c) Web browser

Figure 12: The ultimate purpose of any data management system is to convert data, such as video sequences, into information, such as target identities, locations, and snapshots (b). That information can then advertise its existence to surveillance analysts and operational commanders by linking itself into a browsable and searchable network. Operators can then use a geographically-based browser with clickable icons (a) to link specific map locations to that information. Common tools such as Netscape (c) support exploration of more abstract "information spaces".

6 FUTURE CHALLENGES

Not surprisingly, this research has raised as many questions as it has answered. The problems of accurately geocoding, correcting, and mosaicking the raw data are well in hand, but the problems of extracting information from the data and presenting it efficiently to the user are an ongoing challenge. Three of the most important challenges are

- **Visualizing Temporal Relationships:** how can a two-dimensional computer screen adequately display the relative times of image collection and target detection? How can the operator better visualize motion, speed, and time-horizons?
- **Automated Image Understanding:** more work needs to be done in automated target detection, site modelling, and terrain classification. Algorithms need to be robust to changing illumination and view angles.
- **Common Frameworks for Data Fusion:** current data fusion algorithms are very sensor-specific. Can the critical parameters be identified and extracted so that data fusion algorithms can be more source-agile?

7 SUMMARY AND CONCLUSIONS

UAVs are data-rich but context poor. They provide a very dense stream of images wherever the camera is pointing, but little information about the surrounding world or previous flights in the same area. Accordingly, many of the research topics in this paper have focused on presenting UAV information in spatial and temporal context:

- Geocoding and coregistration tools allow incoming images to be viewed in the context of a topographic map of an area;
- Radiometric calibration tools correct the spectral components of the data in support of change detection and mosaicking activities;
- Mosaicking tools fuse multiple frames into a single large image, thus reducing the total amount of data, without removing any information; and
- New user interface tools help operators view images in the context of other images or maps and thus detect features or discrepancies that would otherwise be missed;

Once the data has been placed in context, tools can be applied to squeeze as much information as possible from it. Research has been done into tools such as the following:

- A change detection tool that can be easily reconfigured for new missions, and that extracts records suitable for storage in a geographic information system;
- A super-resolution tool that fuses multiple video frames together to form a higher-resolution image; and
- A web-based information management tool that allows each piece of information to "advertise its existence" to the operator.

The value of these new tools can only be proved in the context of operational experience. The important next step is to integrate the tools into next-generation UAV ground stations and then improve the technology in response to expressed preferences of the users.

8 REFERENCES

[1] Battlespace Inc. "MAE UAV Nomad Vigil" video tape, Arlington, Va., Sept. 1995;

[2] Bier, Eric A., Maureen C. Stone, Ken Pier, William Buxton, and Tony DeRose, "Toolglass and magic lenses: the see-through interface", Proc. Siggraph '93 (Anaheim), Computer Graphics Annual Conference Series, (http://www.parc.xerox.com//istl/projects/MagicLenses/93Siggraph.html) ACM, August 1993, pp 73-80;

[3] Boulter, J.F. "Sub-pixel resolution of targets in imagery from mosaic detector arrays", *Signal and Data Processing of Small Targets*, SPIE Vol. 1698, 1992, pg 151.

[4] Burt, P.J. and P. Anandan, "Image stabilization by registration to a reference mosaic", *Prod. Image Understanding Workshop*, Advanced Research Projects Agency, Nov. 1994, B.G. 425

[5] Cheeseman, P., R. Kanefsky, R. Kraft, J. Stutz, and R. Hanson, "Super-resolved surface reconstruction from multiple images", *Technical Report FIA-94-12*, NASA Ames Research Center, www://ic-www.arc.nasa.gov/ic/projects/bayes-group/group/super-res, December 1994

[6] Davenport, M.R. and Charlene T. Sailer, "Software techniques for automating multispectral change detection", *ISSSR* '95, International Society for Photogrammetry and Remote Sensing, November 1995

[7] Dutkiewicz, M., "SAR shape correlation for region-based matching of SAR/optical imagery", *Proc. Fusion of Earth Data*, Cannes, France, Feb. 1996.

[8] Dutkiewicz, M., M.R. Davenport, M. Rey, J.F. Boulter, and A. Blanchard "Fusion of optical, infrared, and radar imagery for coastal surveillance", *Proc. Aerosense 96, Infrared Technology and Applications XXII*, SPIE Vol. 2744, April 1996.

[9] Joint Tactical UAV Project Office, "JT-UAV Vision", (http://www.jtuav.redstone.army.mil/uavpp.htm), May 1997.

[10] Lévesque, M.P. "A super-resolution technique for microscanned image sequences", *DREV Report 4738/94*, Defence Research Establishment Valcartier, Quebec, May 1994.

[11] Patti, J. Sezan, M.I., and Tekalp, A.M. "Superresolution video reconstruction with arbitrary sampling lattices and nonzero aperture time", *IEEE Trans. Image Processing*, vol 6, pp. 1064-1075, August 1997.

[12] Pelletier, M., A. Sakamoto, C. Tessier and G. Saintonge, "Autonomous navigation and control functions of the CL-327 VTOL UAV", *NATO AGARD Mission Systems Panel 8th Symposium*, Athens, October 1997.

[13] Sailer, C.T., E. Eason and J. Brickey, "Operational multispectral information extraction: the DLPO image interpretation program", *PE&RS*, Feb. 1997, pp 129 ff.

[14] Wehn, H., P. Wort and N. Goldstein, "Accurate coregistration of remote sensing imagery", *ISSSR* '95, International Society for Photogrammetry and Remote Sensing, Nov. 1995.

[15] Wehn, H. and B. Robertson, "On the use of the object-oriented paradigm for multisensor geocoding", *Proc. ISPRS*, Vol XXIX, Part B4, pp 130-134, 1992.

Unmanned Tactical Air Vehicles - An Electronic Combat Perspective

S.J. Langham B.Sc. and P.M. Zanker Ph.D., C.Eng.
Weapons Sector, DERA
Farnborough, Hants, GU14 OLX, United Kingdom.

ABSTRACT

This discussion paper, arising from project work at UK DERA, considers UTAVs from an electronic combat perspective. The paper will focus firstly upon their application to Electronic Combat roles, and secondly upon the problems of UTAV self protection by means of Defensive Aids Subsystems (DASS).

UTAVs will find a variety of roles in the military operations of the future, both in conflict, and in operations other than war, such as peace-keeping and humanitarian aid. This paper identifies in general the various roles and scenarios which may become applicable to UTAVs. Current UTAVs are predominantly used for reconnaissance, however their near-term rôle is expanding to encompass communications relay, electronic warfare, environmental monitoring, target designation and the suppression of enemy air defences (SEAD) applications.

The paper addresses the SEAD scenario, sensor payloads, airframe performance requirements and levels of threat faced.

The SEAD rôle presents a particularly high risk for airframe survivability, as the UTAV is challenging the very threats which may be used against it. Such UTAVs are likely to carry advanced payloads, making for a high-value vehicle, requiring some measure of self-protection.

Defensive aids will therefore feature in UTAV system designs. It is important to match the style of defensive aids to the roles and concepts of operation of the various types of vehicle envisaged. The style of self protection may be biased towards threat avoidance, confusion of air defences, or towards the countering of immediate threats. The paper discusses these styles of defensive aids systems, their cost and system drivers, and the types of components needed to realise them.

The defensive aids suites could in most cases have to operate without manual intervention, and in this respect will be rather different to the traditional systems found in manned aircraft. The paper discusses these differences, and their implications in terms of system cost, complexity and effectiveness.

The style of any countermeasure responses proposed for UTAVs may vary considerably according to the type of operation and the rules of engagement. Consideration must be given to the dangers of collateral damage, and even environmental damage, in certain circumstances. The paper discusses these considerations.

1. INTRODUCTION

The term "electronic combat" covers the non-image-forming military use of the electromagnetic spectrum. It includes all aspects denying, confusing or deceiving the enemy's use of the EM spectrum, and the exploitation of his use of the EM spectrum to one's own advantage.

Electronic combat covers passive RF sensing, defensive RF & EO alerting and countermeasure systems, RF and EO stealth, directed energy weapons and all types of jamming system.

It is the defensive aspects of EC which relate to the protection of strike aircraft; SEAD is one element of a layered EC defensive structure.

Long range electronic surveillance measures (ESM), electronic intelligence (ELINT), and reconnaissance, information, surveillance and target acquisition (RISTA) provide the first element of this layered structure. Their deep probing of the hostile territory reveals threats to friendly forces such as air defence units (ADUs). This information can be fed into mission planning which ensures that friendly aircraft can avoid the most lethal of the known threats.

Where mission planning alone is insufficient to protect a raid, non-mobile threats can be suppressed by the use of long range precision stand-off weapons, such as cruise missiles, or by whatever destructive means is most appropriate to the circumstances - attack helicopters, artillery, battle tanks, infantry or dedicated air strikes.

Despite mission planning, a raid is likely to overfly previously unknown defences, or mobile defences which have redeployed. These systems may be engaged by lethal SEAD mechanisms such as the anti-radiation missiles (ARMs), or suppressed by jamming (ECM). It is hoped that in the future, target detection systems will become sufficiently accurate to allow conventional weapons to engage ADUs, rather than the traditional use of ARMs, which are becoming prohibitively expensive. Suitable sensors may well be deployed upon stand-in platforms.

Unmanned tactical air vehicles are well suited to this rôle of target location for SEAD, not only due to the usual "D3" demarcation of Dull, Dirty and Dangerous missions, but in this case a fourth 'D' that the authors propose - *Dollars.* The UTAV based sensor, backed up by conventional weapons is suggested as a more cost effective solution than ARMs for dedicated tactical SEAD missions.

Paper presented at the AGARD MSP Symposium on "System Design Considerations for Unmanned Tactical Aircraft (UTA)", held in Athens, Greece, 7-9 October 1997, and published in CP-594.

If the SEAD approach above fails to clear a corridor for a raid, and hostile air defence weapons are launched, then on board DAS is invoked as the final layer of protection for the raiding aircraft. The applicability of DAS to the UTAV platform itself is the subject for the latter part of this paper.

2. TACTICAL SEAD

The term "SEAD" (Suppression of Enemy Air Defences) is applied to the degradation of enemy air defences, broadly speaking, this is defined as the suppression of hostile air defence elements which may engage penetrating friendly aircraft, before an anti-aircraft missile or gun is fired.

Tactical SEAD does not include the pre-strike attack of static air defence assets, such as the destruction of long-range surveillance radars by the use of cruise missiles.

Current capabilities in tactical SEAD rely for the most part upon ARMs, and upon stand-off jamming.

An ARM is launched once a threat is indicated, and flies ahead of the strike aircraft. The missile will search for air defence radar emissions and home onto the highest priority threat. ARMs are capable systems and are combat proven, but there are some drawbacks for the tactical SEAD rôle:

- An ARM can only engage targets which are radiating. If an ADU does not switch on its radar, then an ARM cannot detect it as a target. If the threat of ARMs prevents a radar from switching on, then the radar is considered suppressed, as ADUs are generally unable to engage friendly forces without some radar emission. It is the threat of the radar being switched on to engage friendly aircraft, *after* the passage of an ARM which concerns SEAD effectiveness.

- To maximise the probability that an ADU is suppressed, it is likely that more than one ARM is used against each target. As current ARMs have no battle damage assessment capability, it is not possible to be certain that the engaged threat has been eliminated. The advent of an ADU stopping radiation at the same time as an ARM strikes does not preclude the ADU operators having switched off their radar.

- ARMs are extremely expensive weapons. In a US report (published on the internet) of weapon costs from the Gulf War, unit costs were given for the following weapons. Their warheads are assessed as broadly similar in lethality:
  - AGM-88, HARM, Anti-radiation missile: unit cost $257,000
  - AGM-65E, Maverick air to ground guided missile: unit cost $101,000
  - Mk-82 'iron' bomb: unit cost $498

From the weapon costs stated above, it is apparent that if a cheaper weapon could be delivered to the target area, then the cost-effectiveness of the SEAD operation would improve considerably.

It is the concern that a considerable investment is expended with each launch of an ARM, regardless of the weapon effectiveness, which has prompted research at DERA UK into future SEAD systems.

In its purest form the future concept is to utilise a stand-off sensor to detect hostile ADUs, and then to direct conventional weapons onto the target. If it is considered desirable to reuse this sensor, or at least to utilise its capability against a number of successive targets, then a long endurance sensor platform is required.

This stand-off sensor platform could be a conventional manned aircraft, however the SEAD rôle is traditionally considered the most dangerous of offensive missions, as the SEAD target is specialised at eliminating aerial threats. A natural choice for a platform is the UTAV. An uninhabited air vehicle removes the risk of pilot casualties, and the size reduction brought about by removing the man from the airframe, enhances platform survivability.

3. SEAD OPERATIONS

Target detection is required for all SEAD concepts. Tactical SEAD implies the use of an airborne sensor suite and the provision for some means of attacking threat ADUs. The attack methodology may be either lethal or non-lethal. The definition of a non-lethal strategy is taken as any strategy where there is a reasonable expectation that there will be no loss of human life. An example of a non-lethal attack is stand-off jamming.

An attack platform may be a conventional strike aircraft, or some surface - based system. It could of course be an unmanned combat air vehicle (UCAV), or the sensor platform itself.

In OOTW it is possible that only the target location element of a lethal SEAD system would be compliant with the rules of engagement. This would yield valuable intelligence information, yet would still require some levels of self protection, since the UTAV is likely to be seen as a target of opportunity, or even of high priority, for hostile air-defences.

4. UTAV AIRFRAME

Future tactical SEAD will be operated as a mission support utility. That is to say that it will directly enhance the survivability of specific missions in a timely manner, rather than be used in the 'search and destroy' role.

It may be assumed that fixed ADU sites will be detected ahead of the raid by conventional reconnaissance means. However, it is the mobile ADU threat which is the most significant. Modern mobile ADUs are extremely capable weapons, and any intelligence reports of their position are likely to be stale by the time an offensive mission is launched.

4.1 Range Requirement

The UAV selected must be able to detect threats against friendly aircraft for the whole mission. This may be achieved either by using a static airframe with a long-range sensor, or by use of a long-range airframe with a short(er)-range sensor.

The problems associated with terrain masking at long ranges will almost certainly shift the balance of decision towards a longer range stand -in platform.

4.2 Altitude Requirement

An ESM sensor exists to detect radiation from ADUs, it must be flown at an altitude suitable to intercept such radar energy. This precludes very low flying platforms, as they will be shielded from such radiation by local topography. Equally, platforms which fly too high will be above the area searched by ADUs and would be reliant upon intercepting the very low power sideband emissions, rather than the comparatively high-gain main-beams. This leaves the airframe designer with a medium altitude platform.

4.3 Velocity Requirement

If the SEAD system is to provide timely threat information, and is using a short or medium range sensor, then it can be inferred that the platform must be capable of speeds broadly similar to those of the strike aircraft. A slow flying UAV far ahead of the raid may be unable to detect a mobile threat which has arrived at a point covered by the SEAD sensor an hour ago, but not yet overflown by the raid aircraft.

4.4 Payload Considerations

Payload considerations must also be addressed for the platform. There must be sufficient power and load reserve for the chosen sensor. If the UAV is intended to engage targets with weapons launched from its own airframe, then there must be sufficient scope in airframe design to allow for this.

4.5 Stealth

The airframe design should avoid features which will advertise its presence on the battlefield. A low radar cross section will limit the detection range for radar, whilst a low thermal signature will enhance stealth against thermal imagers.

The sensor suite chosen may avoid active systems to compliment a basic stealthy design. If active sensors are essential for the mission, then stealth of the airframe will fall in importance.

4.6 Performance Summary

In summary the required airframe is likely to have good endurance, fly at high speed (but retain a low speed capability) and at a medium altitude. It may have a low observable profile, and have a reasonable payload capability. One commercially available airframe, which exhibits such features, is the Teledyne Ryan "Scarab" (See Appendix A).

5. UTAV SEAD SENSORS

Sensors technologies applicable to the SEAD field fall into two broad categories; passive and active. If a stealthy airframe is required, then all emissions should be minimised. This suggests the utilisation of a passive sensor. The following section will summarise some of the passive sensor options for a UAV based SEAD sensor.

5.1 Passive sensor technologies

Acoustic

Acoustic signatures have successfully been used in the attack of AFVs. However these are very short range sensors and it is unlikely if current technology can differentiate between an AFV and an ADU based upon the same chassis. It is in doubt whether a motionless ADU will have a sufficient acoustic signature to allow detection.

Passive RF detection

This is the traditional means of sensing used by ARMs, and in ESM and ELINT. Emitted radiation is detected, and the source position calculated. ADUs can only be detected if their radars are switched on; emission control measures (EMCON) will inhibit the performance of such sensors. The utility of these sensors will be greatly enhanced by the use of radar decoys or similar, to encourage the hostile ADUs to illuminate.

Imaging Infra-red

This system obtains a high resolution image of the battlefield and automatically detects likely targets by their thermal contrast and outline. It may prove difficult to differentiate between AFVs and ADUs, but it will produce a near complete set of possible targets. Poor weather will degrade the performance of this sensor significantly.

Optical

Perhaps the best means of differentiating an AFV from an ADU is to have a man in the loop. Both daylight and thermal TV are viable options. An operator cued onto a target can identify the threat and authorise engagement. Again, poor weather degrades performance significantly.

Passive Sensor Summary

The only automated system which will detect all likely threats is the imaging infra-red. This used in conjunction with a passive RF seeker for cueing or differentiation would give the basis for a SEAD sensor suite. However this would not provide an all weather system.

5.2 Active Sensor Technologies

Retro-reflection

A scanning laser detects a reflected flash from an optical lens or camera. This sensor can detect only systems which contain the sensor in their field of view. However any air defence system tracking the sensor platform would give a decisive signature. Again, in common with optical systems, poor weather will significantly degrade performance.

Millimetric Wave Radar

A high-resolution radar system widely employed in the attack of AFVs, this system would be equally effective for the detection of ADUs. It is a comparatively short range system but has all weather capability.

Lidar

A form of high resolution radar using lasers. The high fidelity may allow identification of the targets, but poor weather performance, and short range, are the major disadvantages.

Synthetic Aperture Radar

This is a long-range medium-resolution radar system also used for the detection of armour. It is unlikely that current technology can differentiate between AFVs and ADUs, but a SAR sensor will deliver a complete set of possible threats.

Active Sensor Summary

Active systems can give the required all weather capability, but, in common with passive systems, no one sensor is a robust solution of the detection problem. It is likely that a suite of sensors will be required. SAR offers the best combination of range, detection probability and all weather capability, with the disadvantage of poor differentiation between AFVs and ADUs. Passive RF will show ADUs, as they alone will be searching the sky with radar. Retro-reflection will show EO threats, but only those systems which have the sensor in their field of view. Lidar or mmW offer high resolution signatures which may be used to identify SEAD targets.

6. SEAD SENSOR CONCLUSION

It would appear that the most robust solution is for a sensor suite with at least one active element. It is doubtful whether it is sensible to pursue a highly stealthed airframe if active sensors are to be used.

7. SURVIVABILITY

One of the four key motivations ("D4") for the interest in UTAVs is to have the capability of sending advanced instruments or effectors into hostile or politically sensitive areas, without risk to allied personnel ("Dangerous"). The range of potential UTAV solutions is immense; from the micro-miniature covert surveillance device to the uninhabited large aircraft used to drop relief supplies. The common factor is that the level of risk to the air vehicle, in the desired role, is greater than would be acceptable for a manned equivalent.

The style of UTAV likely to be deployed in an electronic combat role will tend towards the medium sized, but costlier end of the UAV spectrum.

The principal task for an electronic combat UTAV may be one of accurate location of hostile emitters, at long range. The payload would include a high performance, high sensitivity ESM system (the sensitivity may be relaxed somewhat from that of the most advanced manned air systems due to the inherent stealth of the UTAV platform, and the higher level of acceptable risk too the platform). Advanced ESMs are neither cheap nor light weight, however their demands for primary power are not great.

If passive location of emitters is insufficient, then active imaging sensors such as SAR may be required. Alternatively an EC UTAV could be employed as a stand-off RF jammer, supporting a manned raid.

Such active payloads would be technologically advanced, costly, heavy and require considerable power. The high demands for primary power would in turn increase the size and weight of the airframe, or limit the effective range and endurance of the UTAV.

These styles of UTAV will represent high value targets for the enemy air defences, and although more expendable than the equivalent manned asset, they will be too valuable to be regarded as single - use platforms. Thus there will be a requirement for some level of self protection or DAS. The threat environment may be divided into 4 main areas:

- RF threats - short, medium and long range, all weather weapons
- IR threats - short, medium and long range, good weather or clear air weapons
- Laser and Optical threats - short range (line-of-sight), good weather weapons
- Unguided weapon threats - short range only

8. STYLES OF SELF PROTECTION

The traditional concepts of DAS for manned platforms has focused upon detecting and countering immediate threats from missiles and guns - when the platform is under attack, the first priority is survival, and system designs have reflected this imperative. As such, the traditional DAS elements such as radar warners, and the RF countermeasures such as jamming, and the dispensing of chaff, have been of prime importance. More recently, IR countermeasure dispensers, missile approach warners and laser warners have risen in importance, along with IR / optical jamming systems.

A "complete" DAS fit to a UTAV is unlikely to present a cost effective solution except, perhaps, in the case of the most ambitious UTAV concepts such as uninhabited fighter / bombers (i.e. UCAVs) or uninhabited large aircraft.

In order to arrive at the optimum DAS solution for a UTAV it is necessary to take a step back from the traditional concepts, to take a wider view of platform self-protection. We propose here to take a three layered approach toward optimising survivability:

i. The first layer of platform self - protection in any UTAV lies in threat avoidance. Avoidance is achieved by flying outside the detection range, or at least outside the lethal range of the threat. Traditionally this form of protection has been achieved through mission planning and intelligence. In flight, detection by the enemy can be minimised by the use of terrain cover through low flying, and by the stealth of the platform. Cloud may be used against IR and optical detection. Long range passive sensing of un-surveyed threats, permits in-flight re-routing of the mission;

ii. The second layer of platform self - protection lies in minimising the danger that a threat can pose. A SEAD kill (hard or soft) may be invoked from supporting assets or using weapons carried on the platform, if any. The platform can attempt to confuse enemy surveillance and acquisition systems by the use of ECM and decoys. Stealth can be enhanced by flying in the Doppler notch around a threat radar, and by making use of cloud cover against IR and optical seekers. The flight altitude can be chosen to avoid the bulk of short range threat systems. Where it is not possible to avoid or suppress detection, indeed if the mission requires the platform to provoke or attack a threat, then it is feasible to select the most favourable approach geometries, to minimise exposure and to deny engagement opportunities to the enemy.

iii. The third layer of this approach of platform self - protection is the traditional DAS layer, which is invoked only if a threat is engaging the platform. Here the traditional components providing close-in threat warning, such as RWR and MLAW, and more recently LWR, come into play. Countermeasure effectors such as RF and IR jamming, chaff, flares and other expendables are used to break tracking lock or to decoy an incoming missile.

The UTAV concepts of operation may limit the applicability of layers (i) and (ii). This and other issues of self-protection and DAS will now be discussed in more detail. Protection against surface based, and airborne threats will be dealt with separately.

9. SURFACE-BASED THREATS

A wide range of surface-based systems could potentially threaten a UTAV. ADUs may be found in fixed locations, be ground-mobile, ship-borne or man-portable. Missile systems may be guided using active or semiactive RF illumination, laser illumination, command-to-line-of-sight principles, or make use of passive imaging or hot-spot detection. Anti-aircraft guns can derive aim points from radar, laser or passive EO / IR tracking systems, or be aimed by an unassisted human operator.

An enemy's air defences may consist of a haphazard array of individual ADUs, with little or no co-ordination of assets. Such situations are most typical of insurgents, terrorist or criminal groups, and encountered in peace-keeping operations or low - intensity conflict.

Alternatively, the air defences could be well co-ordinated through a clear structure of command and control, making use of early - warning and long range surveillance assets to pass on target vectors to the appropriate ADU networks.

9.1 Threat Avoidance

The avoidance tactic is a basic and obvious one for enhancing the survivability of all types of air platform. The nature of the mission of a UTAV for electronic combat, however, tends to reduce the scope for threat avoidance.

A UTAV employed in long range passive sensing of emitters must have a clear view of them, hence low flying and the use of terrain cover are not compatible with the mission, except when ingressing to, and egressing from, the target area.

Data on the locations of possible threats is likely to be scant, since it is the role of the UTAV to be the instrument of gathering such intelligence. The data collected by the UTAV may, however, be used on board to re-route around the most lethal threats detected, and of course passed back to any manned aircraft that the UTAV may be supporting. Organic support of a manned raid would, however, preclude any re-routing that the raid itself could not follow.

The UTAV is likely to be inherently more stealthy than a manned platform. The airframe will typically be smaller, and engine thrust requirements and power use less. Thus both RF and EO signatures will be simpler to reduce. Advanced stealth will, however, remain difficult and costly to achieve. The role of the UTAV in collecting ELINT could require it not to be over - stealthy in the RF; part of its function would be to provoke silent emitters into action.

RF Stealth

The stealth trade-off in the RF thus becomes a choice between two alternatives:

i) A platform with little or no special stealthing in the lower RF bands used by surveillance and acquisition radars. Such a platform would be vulnerable to attack by RF systems, so require some DAS elements. Some stealthing would enhance DAS effectiveness, particularly in the higher RF bands used by tracking and fire-control radars, and by airborne-intercept radars;

ii) A highly stealthed, hence more costly platform with low vulnerability to threats, but requiring that threats be provoked into action. This provocation could be achieved in either of two ways:

- Deploying some additional UAVs or expendable RF decoys to fly ahead of the UTAV;

- Alternatively the stealthy UTAV could carry an ECM on board, used to present intermittent targets to surveillance radars.

A UTAV carrying an active sensor such as a SAR, or a stand-off RF jamming capability, will be highly detectable when transmitting, so there would seem to be little point in expending great efforts towards passive RF stealth. It will be trackable by enemy ESM and potentially at risk from long range IR-guided missiles, or ARMs.

EO/IR Stealth

EO / IR stealthing will be a key feature in any UTAV optimised for electronic combat. If the UTAV is easily detected and tracked in the visible optical or the IR, then it will fail in its mission of provoking hostile RF emissions, and is more likely to be engaged by IR systems.

Many EO / IR threats, MANPADS in particular, will only be detectable when they launch missiles or fire their guns. To deliberately provoke this would place the UTAV under very great risk. Such a mission would more effectively be undertaken by lower cost expendable platforms, perhaps flying a few minutes ahead of a manned raid.

The bulk of mobile EO / IR systems associated with mechanised infantry or armoured formations, are short range point defence weapons. The UTAV may avoid most of these by flying at a medium altitude. The presence of low cloud would in any case mask the majority of EO / IR threats, and the UTAV could make use of cloud for reduced altitude flying, if cloud were present and reliably detectable. High altitude flight would introduce the risk of leaving a vapour - trail which would severely compromise stealth in the visible wavebands.

9.2 Minimising Danger

If the UTAV platform is detected by a threat radar, it is in danger. This danger could be reduced by avoidance tactics, but assuming that avoidance is not possible or not desirable at some phase of the mission, then there remains the possibility of confusion of the surveillance. The objective is to protect the platform by degrading the threat's ability to hand over from detection to tracking.

This may be achieved by some combination of stealth in the high RF bands typical of tracking and fire-control radars, ECM, and decoys. The optimum point in the cost - performance trade-off will be dependent upon the role of the UTAV.

Stealth can be enhanced against a particular threat radar by flying in its Doppler or MTI notch. If the radar *must* be approached, then stealth can be enhanced by flying slowly, placing the UTAVs Doppler or MTI return closer to that of the ground clutter. If an RF jammer is carried for a raid - support role, then an ECM capability for self protection may be added at minimal cost.

Some styles of UTAV may be required to approach a threat system in order to deliver a lethal payload. In such cases the only remaining option for reducing the risk of engagement is low flying to make the maximum use of terrain screening.

A UTAV flying ahead of a manned raid, will relay threat locations back to the manned aircraft. Pilots may then choose to respond with some form of hard kill, to clear a path for themselves, and of course for the UTAV.

9.3 Countermeasures

DAS countermeasures represent the final layer of platform self - protection, invoked only if a threat is engaging the platform.

The major threat systems challenging UTAVs used in ELINT or stand-off jamming will employ RF guided medium to long range missiles. The principal RF alerting device in traditional aircraft DAS is the radar warning receiver (RWR), giving both the type of threat and its direction of arrival. Now the EC - UTAV will be equipped with an advanced ESM as part of its primary sensor suite, and RWR functionality can be added to ESM at marginal cost. Certainly it would neither be necessary nor cost effective to propose a stand-alone RWR.

Once alerted to a locked on tracking threat or to an incoming active missile seeker, the simplest countermeasure is to turn to place the threat on the beam. This has the effect of placing the platform in the Doppler or MTI notch of the threat radar, and combined with the platform's low inherent signature may have some success in breaking lock.

Manoeuvre is a simple and cost effective countermeasure. More robust countermeasures are feasible but introduce additional cost and weight penalties.

<u>Chaff</u> has been used as a counter to radar systems since the second world war. The use of chaff for *self screening* can be effective in the case of slow moving assets, such as air-ship-type UTAVs. The principal self-protection use of chaff from a UTAV would, however, be as a decoy target, in conjunction with UTAV manoeuvre, to break the lock of a tracking radar. Chaff is not costly, but it is expendable, implying a weight and volume a trade-off in the number of shots of chaff which are to be carried on a mission.

<u>RF Jamming or ECM</u> offers a wide range of techniques to counter RF threats. Systems are costly, but if restricted to the role of self-protection jamming, weight and power use can be contained within reasonable limits. ECM has the advantage over chaff of being re-usable, it also offers additional functionality in support of the UTAVs primary ELINT role.

The problems associated with protection against EO, IR and laser-guided threats are considerable. The bulk of such threats will not alert the UTAV in any way until a missile is launched or a gun fired. Thus a missile launch and approach warner becomes highly desirable, particularly in protecting a costly UTAV such as one carrying both ESM and SAR.

Flares of some sort would be the most practical countermeasure reaction to a missile alert. Flares, like chaff cartridges are expendable, implying a weight and volume a trade-off in the number of shots to be carried.

If anti-air ARMs are considered a threat then EMCON (i.e. switch off of all active RF devices) plus manoeuvre must be invoked along with flare deployment - an MLAW cannot distinguish between an IR guided missile and an ARM.

IR jammers tend to be costly and bulky, however there is one style of jammer which does not require the addition of a missile approach warner to cue its operation. Such un-cued jammers compromise stealth in the IR bands, and, without the presence of a MAW, there would be no warning of nor protection against ARMs.

Laser Warning Receivers are practical, and need not be particularly bulky. They can effectively alert the UTAV to the presence of laser threats of all types.

In summary, the favoured solution against surface-based EO, IR and laser-guided threats is avoidance wherever possible. DAS - style warners and countermeasures impose penalties in terms of cost, weight and volume, however in the case of UTAVs carrying costly active RF payloads, these penalties are likely to have to be borne.

10. AIRBORNE THREATS

The prospect of an electronic combat UTAV encountering fighter aircraft is realistic only when facing a sophisticated enemy possessing a well co-ordinated air defence network, and an efficient airforce. In such circumstances, however, the threat from manned aircraft is a considerable one. Enemy airborne interceptors are likely to carry a mix of medium to long range air to air missiles both RF and IR guided, and possibly air-to-air ARMs. Additionally they may carry cannon for close combat, and can make use of their jet-wakes to disrupt light air vehicles.

Anti-air helicopters would pose little threat to any UTAV flying at medium altitude, unless equipped with an advanced "look - up -shoot - up" capability.

UTAVs employed in organic support of raids will be followed by manned aircraft. We can assume that the raid's strike aircraft will represent the highest priority targets for the enemy interceptors. A raid likely to encounter such opposition will typically include fighter aircraft to deal with enemy interceptors.

10.1 Threat Avoidance

The typical UTAV will not be able to out run or out fly a fixed wing interceptor aircraft. Consequently, any avoidance strategy must rest upon avoiding detection by the long-range systems used to vector the fighters to their target, and upon detection by the fighters' airborne intercept radar and IR search and track systems. Ultra high altitude operation is a possible strategy, but largely outside the scope of UTAVs for electronic combat.

These considerations push toward the more stealthy UTAV options, making use of off-board decoys or on-board ECM for the prime task of provoking the air defences into action. If the UTAV cannot be detected by long range systems, then fighters cannot be vectored against it . If there is a significant risk of fighters being vectored towards the UTAV, then we can consider reducing the tracking accuracy of detecting system, with some mix of stealth, low speed flying, manoeuvre and ECM. Enemy airborne early warning radars are likely to have the ability to form high quality tracks, hence ECM efforts should be directed towards them.

10.2 Minimising Danger

Assuming that the UTAV can successfully deny high accuracy tracking to the enemy, then incoming fighters will have to search for the UTAV using AI radar, and IR. Against these threats, stealth in the high radar bands, and in the IR, become most important.

The SEAD or ELINT UTAV will carry ESM / RWR to warn of the presence of hostile Airborne Interceptor radars. The danger they present may be reduced by presenting the AI radar with the minimum radial velocity. This may be achieved by turning to place the threat on the beam, and by flying the UTAV at its minimum air speed. Some forms of ECM may also be appropriate.

At close quarters the enemy pilot will try to acquire the UTAV visually, the stealth emphasis here must be in the visible and IR bands, ensuring minimum observability.

10.3 Countermeasures

The responses to a locked on RF tracker, or an incoming RF missile, have been discussed above, and are really no different with regard to air-to-air threats. The platform must, however, face the possibility of a medium or long range shot using an IR missile. It was argued above that a suite of IR warners and countermeasures is unlikely to be cost effective, except for a high value UTAV carrying active SAR.

Short range cannon may be effective against a UTAV, but typically it will present a small and difficult target. The jet wake of a fighter, particularly using an afterburner, is potentially destructive over a large volume. There is no DAS countermeasure to this type of attack, but some hardening of the airframe and its aerodynamics may be possible.

Some forms of UTAV will carry lethal payloads for deployment against their ground targets, and in some cases these may be usable against fighter aircraft. The problem lies in the targeting and fire control associated with such a weapon; the solution, if any, is likely to depend upon the presence of remote manual control of the UTAV.

11. AUTOMATED RESPONSES

A UTAV will be required to derive its own defensive responses to the situation it finds itself in. A totally manual style of decision making and control, through remote piloting, is an option, but not an attractive one. Practically, a great deal of autonomy will be required. Key to decision making is knowledge of the environment or "situation awareness".

11.1 Situation Awareness

Situation Awareness is a much used term with a variety of meanings. In the context of an EC UTAV, this paper suggests a definition that

> "Situation awareness comprises an up to date mission library (or database) of own forces, neutrals, targets and threats, in terms of their positions and headings; their identities, their capabilities and technical parameters; their groupings and intentions (as far as can be deduced) and of the priority of each threat."

Situation awareness exists against the background of the UTAV's own position, own mission objectives, the local terrain and local conditions.

In most current manned air platforms situation awareness exists almost entirely in the pilot's mind. Some elements of it exist within the various sensor and effector subsystems, but the pilot alone must perform the overall data fusion task; filtering, summarising and prioritising what he sees. In an UTAV, situation awareness must be implemented as a subsystem, performing data fusion at all levels.

11.2 Data Fusion

Data fusion represents a family of tools and approaches to the problem of forming situation awareness. The term embraces a variety of levels, or areas of interest; for example:

- image fusion at pixel level;
- association of new measurements with each other and with currently tracked entities;
- fusion of measurements and current tracks to form updated kinematic tracks;
- classification of entities by track analysis, and clutter removal;
- fusion of declared identities of entities;
- association of entities into groupings, forming an air-picture;
- fusion of evidence or assumptions of intent, forming threat priorities;
- responses, tactical advice, and reactions

A variety of methods and algorithms exist for the implementation of each level of data fusion. The table below summarises these against the JDL four-layer model of data fusion processes - OODR (Observe, Orient, Decide, React):

Level	Function // Techniques
1 (Observe)	Association (of plots or tracks) // Mathematical techniques e.g. nearest neighbour.
1 (Observe)	Fusion of plots or tracks to form entities // Mathematical techniques e.g. Kalman filters, winning sensor.
1 (Observe)	Classify entities, de-clutter // Pseudo - sensor analysis of track dynamics.
1 (Observe)	Identify entities // Probabilistic techniques e.g. Baysian (STANAG 4162), Dempster - Shafer; Rule - based.
2 (Orient)	Picture formation (entities >> groups) // Rule - based, reasoning tools.
3 (Decide)	Threat Prioritisation // Rule - based, game - playing.
4 (React)	Reactions // Rule - based, hill-climbing, optimal control, database lookup.

11.3 Responses

The end product of data fusion at levels 1 to 3 is a machine held situation awareness. This exists only to be used by the routines which will control the UTAV's responses.

The principal response packages will be:

- Mission re-planning, re-routing to avoid threats whilst fulfilling the mission requirements of data collection, coverage of areas, time on station, and recoverability.
- Tactical manoeuvre control.
- Allocation, timing and control of DAS countermeasures.
- Targeting, allocation, firing and control of any lethal systems carried.
- Moding and tasking of EC and other sensor assets.
- Reporting back of the situation to the command centre responsible for the UTAV mission, and to other interested allied assets.

An overall response control function will be needed to allocate classes of response and resources to each response package. Manual overrides may be allowed if there is remote piloting or decision making.

12. RULES OF ENGAGEMENT

The difficulties associated with the application of rules of engagement to UTAV missions affect both the concepts of operation and the self protection strategy.

12.1 Operations Other Than War

The rules of engagement associated with peace keeping and humanitarian aid operations tend to be the most restrictive, precluding lethal responses in almost all circumstances. A non-lethal UTAV involved in electronic combat is most likely to fulfil a surveillance (ELINT) role. Threats may be faced, so countermeasure strategies must be considered. Threats are likely to be isolated, uncoordinated and, mostly, unsophisticated.

In order to safeguard life and property, any use of DAS expendables must be carefully regulated. Flares pose obvious hazards should they hit the ground burning. At low level, flares would not be an option, although at medium or high altitudes they could be quite safe.

These considerations push the countermeasure strategy towards stealth and threat avoidance. Flying at medium altitude will avoid the bulk of small arms, AAA and IR guided threats. Sophisticated air-defence surveillance networks are most unlikely to be encountered in these operations, but the occasional mobile SAM could be present; indeed locating these will be one of the main objectives of the UTAV mission. The favoured countermeasure against RF systems is ECM. Jamming offers a non-lethal (soft) kill of the launcher (by disrupting the engagement sequence) or of a missile in flight. The missile or its debris will fall to earth somewhere: this is unavoidable.

The use of ECM in operations other than war may be almost unrestricted. The only exception is where it could pose a hazard to civil air traffic. Such hazards should be minimised at the mission planning stage - avoiding civil air lanes. The presence of the UTAV itself in a civil air lane would pose a risk of collision far greater than any risk from its ECM.

12.2 Intense Conflict

War scenarios are not without rules of engagement. The control of UTAVs carrying any sort of lethal payload is problematic, and in the foreseeable future the solution will lie in remote manual intervention.

Parallels may be drawn with cruise missiles and stand-off weapons dispensing submunitions, however there is an essential difference. Stand off weapons are dispatched against a specific target or target area, implying that the surveillance, identification and acquisition tasks have already been carried out and confirmed, and that the mission has been judged safe in terms of its potential for endangering civilians or allied assets. The lethal UTAV electronic combat mission, in contrast, is one of surveying an unknown area, identifying and locating targets (mobile ADUs for example), then attacking. It is most likely that visual confirmation will be required, if, for example, an ADU is located within a built up area, or close to known positions of allied forces.

The lethal UTAV must, therefore, carry two way communications links passing sensor data to a controlling location, and receiving command instructions. It is also likely that IFF and some EO / IR imaging must be carried. Imaging would also allow the lethal UTAV to collect some battle damage information after its attack.

The problems of controlling non-lethal UTAVs are less severe, however DAS countermeasure responses could, in some cases, endanger allies or civilians. Flare and chaff deployments present the same problems in intense conflict as in they do operations other than war, but the level of acceptable risk will be higher. Non lethal countermeasures such as manoeuvre, ECM and IR jamming will be preferred over other forms, as these present the least risk to allies and to civilians.

13. ACKNOWLEDGEMENTS

The work reported in this paper was carried out for the UK Ministry of Defence under the Applied Research Programme.

14. STATEMENT OF RESPONSIBILITY

Any views expressed in this paper are those of the authors and do not necessarily represent those of the UK DERA, nor of H.M. Government of the United Kingdom.

GLOSSARY

ADU	Air Defence Unit
AFV	Armoured Fighting Vehicle
AI	Airborne Interceptor
ARM	Anti-Radiation Missile
D3	Dull, Dirty and Dangerous
D4	Dull, Dirty, Dangerous, and Dollars
DAS	Defensive Aids Suite(s)
DASS	Defensive Aids Sub-System(s)
DERA	Defence Evaluation and Research Agency
EC	Electronic Combat
ECM	Electronic Counter-Measures
ELINT	Electronic Intelligence
EM	Electro-Magnetic
EMCON	Emission Control
EO	Electro Optic
ESM	Electronic Surveillance (or Support) Measures
IR	Infra Red
JDL	Joint Directors of Laboratories
LWR	Laser Warning Receiver
MANPADS	Man Portable Air Defence Systems
MLAW	Missile Launch and Approach Warner
mmW	millimetric wave (radar)
MTI	Moving Target Indication
OODR	Observe, Orient, Decide, React
RF	Radio Frequency
RISTA	Reconnaissance, Information Surveillance and Target Acquisition
RWR	Radar Warning Receiver
SAR	Synthetic Aperture Radar
SEAD	Suppression of Enemy Air Defences
TV	Television
UAV	Uninhabited Air Vehicle
UCAV	Unmanned Combat Air Vehicle
UTAV	Unmanned Tactical Air Vehicle

APPENDIX A - Example Platform

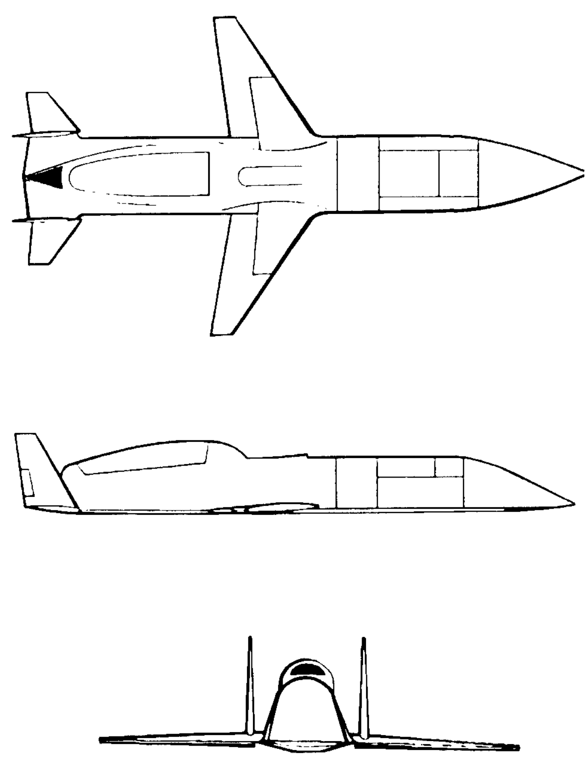
Name:	Scarab
Company:	Teledyne Ryan, USA
Status:	In service (Egypt 1988)

PERFORMANCE & DIMENSIONS

Range:	1000 km
Altitude ceiling:	13100m (42900 ft)
Maximum speed:	235 m/s (460 Knots, 530 Mph, 850 kph)
Length:	6.15m
Wingspan:	3.35m
Height:	0.86m
Maximum weight:	1077 Kg
Launch:	Rocket assisted take-off (RATO)
Recovery:	Parachute and airbag
Propulsion:	1 x Teledyne CAE 373-8c Turbojet
Guidance:	Inertial and GPS navigation, pre-programmed or by remote control

PAYLOAD

Payload weight:	131.5 Kg
Payload:	Storage daylight camera / TV / infrared line scanner



Small Effective Air-to-Surface Munitions for Unmanned Tactical Aircraft Applications

D. R. Brubaker
Wright Laboratory Armament Directorate
Munitions Assessment Division
Technology Assessment Branch (WL/MNSA)
101 West Eglin Blvd, Suite 326
Eglin AFB, Florida, 32542-6810
USA

1.0 SUMMARY
This paper describes two emerging munition technologies beneficial to Unmanned Tactical Aircraft (UTA) and attempts to define a necessary weapon load capability. To determine a weapon/loadout combination that maximized the lethal effectiveness of an UTA while minimizing the payload weight required, a mission level analysis was conducted and concludes that a minimum of 1000-lb (454 kg) of payload provides an UTA a viable air-to-ground combat mission capability. A 2000-lb (908 kg) payload provides an increased effectiveness but must be contrasted with the associated increase in UTA cost, size, weight and propulsion needed to employ the additional payload weight.

2.0 INTRODUCTION
As the name implies, an Unmanned Tactical Aircraft (UTA), has a mission requirement to provide a combat capability as opposed to only a non-combat mission role, such as providing reconnaissance, surveillance, or assessment of battle damage to enemy targets. Currently, to provide a combat capability against fixed-soft, fixed-hardened and stationary ground targets, the UTA must be capable of carriage and deployment of air-to-surface munitions. Unfortunately, a payload capability equivalent to only one 2000 pound (908 kg) class munition may require the UTA design to increase in size beyond what is acceptable with respect to cost and/or logistic goals. Smaller, high precision, autonomous munitions have been envisioned to provide the UTA with a desired level of combat capability. Enabling technologies being developed and demonstrated in US Air Force laboratories are beginning to provide new small weapon systems well suited to an UTA role. It is clear that a selection of munition options for UTA operations is critical to maximizing the utility and mission. Additionally, a system engineering approach is necessary to ensure that the munitions be incorporated into the UTA design early in the development phase especially since the munitions play such a key role in providing the basis for the desired combat capability.

3.0 MUNITIONS

3.1 Low Cost Autonomous Attack System (LOCAAS)
LOCAAS has successfully merged three newly developed technologies into a weapon that could change the nature of air-to-surface anti-materiel warfare. When the compact airframe design is fitted with a state-of-the-art

Paper presented at the AGARD MSP Symposium on "System Design Considerations for Unmanned Tactical Aircraft (UTA)", held in Athens, Greece, 7-9 October 1997, and published in CP-594.

sensor/seeker, and an adaptable warhead system the results are a highly capable weapon system that puts all fixed-soft, mobile and relocatable targets at risk. LOCAAS offers numerous benefits to the battle managers. Launch platforms will be held out of harms way due to the standoff capability. Platforms carrying twelve LOCAAS units have the lethal capability of 6 platforms each carrying two 'Maverick' missiles. The increase in sortie effectiveness should increase the tempo of the conflict as well.

LOCAAS houses a Laser Detection and Ranging (LADAR) seeker developed to accurately and autonomously acquire, classify, and track targets during the attack. With this capability, LOCAAS scans the battlefield, finds potential targets, and then switches into a "track" mode to differentiate between tanks, trucks, missile launchers and radar sites. Once the LADAR unit determines a valid target the computer selects the appropriate kill mechanism to maximize the lethal effectiveness. The multi-mode, shaped-charge warhead can selectively fire an armor penetrating 'long-rod' if the target is heavily armored, such as a battle tank. If the target is lightly armored or protected by reactive armor the warhead can select a penetrating 'aero-stable slug'. Finally, if the target is 'soft' or thin-skinned like a surface-to-air missile launcher, radar site, or theater ballistic missile, the warhead can operate in a fragmentation mode to distribute lethal fragments over a large area. This unique warhead achieves the three modes of operation by selectively detonating high explosive behind a copper plate. One mode forms the plate into a long rod. The second mode forms the aero-stable slug and the third mode causes the plate to break into multiple fragments.

The LOCAAS, shown in Figure 1, is 30 inches (76.2 cm) long and weighs approximately 100-lbs (45.4 kg). A miniature turbo-jet engine provides 100 nautical miles (185.2 km) range and the ability to search over large areas. The small size provides the ability to package numerous LOCASS units in current and future delivery platforms.

Warhead tests have been completed successfully. Seeker testing is ongoing. A short non-powered flight test has demonstrated the autonomous search, acquisition, target-classification and attack modes. All-up flight tests will occur within the next couple of years. Completion of the LOCAAS development will provide the warfighter a very effective munition to defeat advancing mechanized troops as well as perform missions to suppress enemy air defenses during the early phases of a conflict and open the paths for air-to-surface munitions like the small smart bomb described next.

Figure 1. Full Scale Model of LOCAAS

3.2 250-lb (113.5 kg) Penetrator

At the time of this writing, the operational capability of a 250-lb (113.5 kg) Small Smart Bomb (SSB) concept had recently been demonstrated under the Miniaturized Munition Technology Demonstration Program conducted at Wright Laboratory Armament Directorate (WL/MN), Eglin Air Force Base, Florida. The Miniaturized Munition Technology Demonstration (MMTD) program

had the objective of developing a 250-lb (113.5 kg) class munition that is effective against many of the fixed soft and hardened targets previously vulnerable to only 2,000-lb (908 kg) class munitions. Figure 2 compares the size of the MMTD test vehicle to a 2000-lb (908 kg) class general-purpose munition.

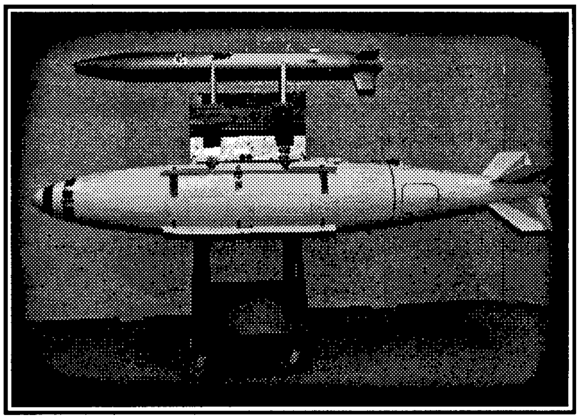


Figure 2. Full Scale Models of MMTD [upper] and 2000-lb (908 kg) [lower]

There are many benefits to smaller bombs, the greatest of which is an increased loadout capability for fighter and bomber aircraft. With each bomb independently targeted and autonomously guided, the number of targets killed by a single fighter or bomber sortie can be tripled or even quadrupled. Besides the capability to increase sortie effectiveness and the number of kills per pass, the smaller volume and weight of 250-lb (113 kg) munitions versus the more typical 2000-lb (908 kg) munition means 3 to 4 times as many bombs can be transported with current airlift capability; allowing a much more rapid deployment of warfighting capability to the region of conflict. Another benefit is that the bomb's accuracy and lower explosive yield will focus the lethality on the target while reducing the potential for collateral damage on friendly forces and noncombatants alike.

While these benefits are evolutionary in nature, a truly revolutionary benefit can occur when aircraft designers take advantage of the smaller munitions and reduce the size of aircraft weapons bays, in turn reducing the size and cost of future aircraft like the UTA.

The MMTD goal was to baseline small bomb technology and demonstrate the operational utility of a 250-lb (113.5 kg) class precision-guided munition. The MMTD munition used a Differential GPS/INS system to achieve a precision guidance accuracy of less than 9.8 feet (3-meters) CEP against a surveyed target. The weapon size requirements [6 inch diameter, 72 inch length, (182.9 cm) and 250-lb (113 kg) total weight] meant that the warhead design space was relatively small. To achieve the reinforced concrete penetration goal of 6 feet (1.8 meters) with a small, lightweight weapon, the warhead was designed with a biconic nose shape. The Armament Directorate-developed Hard Target Smart Fuze (HTSF) has been incorporated into the warhead for determining the optimum detonation point. This fuze has the ability to discriminate between media (concrete, soil, air, etc.) and determine when it has entered a void (room) in a target and then detonates the main explosive charge. The goal of carrying 50-lbs (22.7 kg) of explosive had to be traded off with penetration/survivability goals. The current design allows 42-lbs (19.1 kg) of high-explosive to be packaged in the warhead. The first phase of the MMTD began in September 1995 and was an 18-month effort concluding in March 1997. Ground tests consisted of cannon and sled track testing for penetration performance and arena testing for determining warhead lethality. Five flight tests were conducted culminating in a live drop against a realistic aircraft shelter.
On 25 June 1996, the first penetration and survivability tests of the final warhead design were conducted. The initial test fired the

warhead into a 6 foot (1.8 meter) block of concrete reinforced with 1-inch (2.54 cm) rebar. With an impact velocity of approximately 1200 feet per second, (365.8 meters per second) the warhead successfully penetrated the target and exited cleanly on the other side (Figure 4). After recovery and inspection of the warhead, the only noticeable change was that the paint was stripped off. Since that test, the warhead has been shown to penetrate over 6 feet (1.83 meters) of reinforced concrete and still be survivable at impact velocities above 1400 feet per second, (426.8 meters per second) impact angels of 70 degrees, and angles of attack up to 2 degrees. Additional tests in January 1997 successfully demonstrated the end-to-end function of the warhead with a live Hard Target Smart Fuze (HTSF) and live explosive fill against a 6 foot (1.83 meter) reinforced concrete target.

A series of captive flight test were conducted prior to the five free-flight tests, which began 23 December 1997. The first three MMTDs were released from altitudes of 30000 (9.14 km), 25000 (7.62 km), 40000 feet (12.2 km) and at varying distances down-range and cross-range from the reinforced concrete target slabs. The target slabs, measured 20 feet (6.1 m) by 20 feet (6.1 m) and 3 feet (.914 m) thick rested horizontally on the ground. The bombs all impacted within a 9.8 foot (3 meter) radius from the aimpoint. Impact velocities greater than 1100 feet per second (335.4 meters per second) were achieved with impact angles of approximately 83 degrees from the horizontal and less than a 1 degree angle-of-attack. The MMTD penetrated the 3 foot (.914 m) concrete slab and attempts to locate the warhead from the first tests ended after probing 40 feet (12.2 meters) deep in the soil.

The final flight test was conducted to demonstrate the operational utility of the small bomb concept. Two weapons were dropped one second apart on a single pass against two individual targets separated by roughly 300 feet (91.4 meters). Each weapon successfully guided to their intended target after being released from 40000 feet (12.2 km) altitude. The MMTDs were released over 10 nautical miles (18.52 km) down range and off-axis from the target requiring the weapons to maneuver to impact. The warheads entered overcast weather from 30000 feet (9.14 km) to 2000 (0.61 km) feet thereby demonstrating the all weather capability. After release the pilot turned away from the target and although egressing subsonic, was over 20 nautical miles (37 km) from the target location at weapon impact.

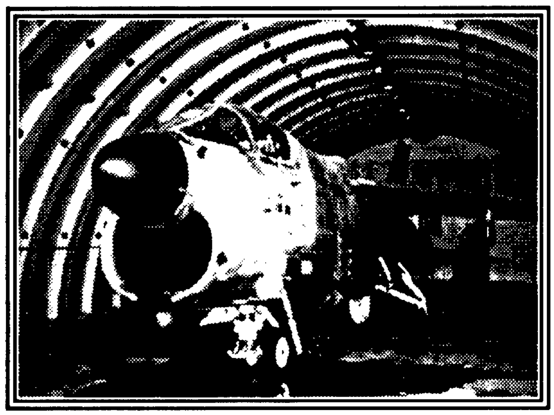


Figure 3a. Pre Test Results

Figure 3b. Post Test Results

One inert weapon demonstrated the folding fin mechanism and successfully guided to its target, which was a dummy aircraft shelter. The second weapon carried 42-lbs (19.1 kg) of tritonal and a live fuze. The aircraft shelter target for this second weapon was covered by roughly 6 feet (1.8 meter) of soil and a layer of concrete. Additionally, a retired A-7 aircraft was parked inside the shelter and the shelter doors were left open for camera coverage of the test. The live warhead guided to the target, penetrated the shelter and detonated at the desired location determined by the hard target smart fuze. Figure 3 reveals the catastrophic damage to the aircraft from the MMTD detonation.

The success of the MMTD program has demonstrated that the technology necessary to develop a small smart bomb is currently available and that the weapon concept can provide a multiple kills-per-pass capability. A second phase of MMTD tests is planned for FY99-02 and may include the integration of a terminal seeker, wing-kit for increased standoff, and anti-jam GPS technology into the baseline weapon. Additional future opportunities to demonstrate the capability of the small smart bomb could include integration of the munition on an uninhabited aerial vehicle (UAV) in the newly formed UAV battle lab at Eglin AFB.

4.0 ANALYSIS

4.1 Munitions

Although small autonomous munitions for both fixed and mobile targets are being developed at Eglin that are applicable for an UTA role this analysis involved only munitions for fixed and relocatable targets. The decision was based on the fact that munitions for fixed targets require greater payload capacity therefore they would drive the UTA weapon carriage requirements. An UTA with a fixed target capability would then also have the ability to carry smaller mobile target munitions, i.e. LOCAAS, described in this report. Three fixed and relocatable target weapons were used in this study, a 1000-lb (454 kg) general purpose, 1000-lb (454 kg) penetrator and a 250-lb (113 kg) penetrator. All munition effectiveness numbers were based on 26 foot (8 meter) and 10 foot (3 meter) Circular Error Probable (CEP) accuracy estimates. The 26 foot (8 meter) accuracy is obtained from an Inertial Navigation System / Global Positioning System (INS/GPS) guidance scheme. A terminal seeker is assumed be required to achieve the 10 foot (3 meter) accuracy.

4.2 Target List

It is important here to define the terminology that will be used to describe targets in this report. Target types include fixed soft, fixed hard, stationary and mobile. Fixed targets include buildings, underground bunkers, aircraft shelters, etc. Each of these fixed targets could be "soft" or "hard". The distinction although somewhat subjective, in this paper refers to whether construction methods are employed specifically to protect the target from damage due to blast, fragment and/or penetration. A stationary target is understood to represent a target that can be moved, but which requires time and dismantling prior to transportation. As an example, a Transporter, Erector, Launcher (TEL) would be considered a stationary target since the launcher requires dismantling and stowage before it can be moved. Mobile targets include trucks, battle-tanks, armored personnel carriers, etc.

A target "type" also can consist of unitary or multiple elements. A unitary target type would be a single building, for example, while a multiple element target type could be a Petroleum, Oils, and Lubrication (POL) field

containing numerous POL storage tanks. Thus, a POL target with 10 POL tanks would be a single target "type" with 10 target "elements". A kill of this POL target would result in up to10 target elements killed. A theater can contain many target types and multiples of each type with each type having one or more elements.

The targets selected for this analysis contained 61 different target types resulting in 3720 total targets and 34930 total elements. Table 1 gives a breakdown of these targets by type and quantity. No personnel or mobile targets were included in this target set.

Target Type	Number of Types	Total Number of Elements
Hard, Fixed	22	1458
Soft, Fixed	32	19828
Relocatable	7	522

Table 1. Target List by Type and Quantity

4.3 Loadout

Various loadout configurations were used with each of the appropriate weapons in this study. Loadouts of 1 and 2 were used for the 1000-lb (454 kg) munition while a for the SSB the loadouts were varied between 2, 4, and 8. By varying the loadout options it was possible to investigate the effect of loadout and to determine an optimum loadout quantity. 2000-lb (908 kg) munitions were not used.

4.4 Methodology

Analysis was accomplished using accepted procedures as defined by the Joint Technical Coordinating Group for Munitions Effectiveness (Air-to-Surface). Standard Joint Munitions Effectiveness Manuals and the "Open-End Methods" (Reference 2) were used throughout.

5.0 RESULTS

Prior to reviewing the results of the analysis it is important to understand the figure of merit used to draw conclusions. The term Expected Kills per Sortie (EKS) represents the ability of a delivery platform to defeat multiple targets on a single sortie and is indicative of the number of weapons that can be carried and deployed by that platform. The average EKS is simply the total number of elements in the target set divided by the total number of sorties needed to kill all the elements in that same target set. It should be remembered that some munitions will be more efficient at defeating some target type/elements, and much less efficient at others. Computing an average will result in a loss of this fidelity, however an average is an indication of the pervasiveness of a munition's effectiveness across all targets

The following figures will provide insight as to the UTA loadouts necessary to achieve a desired level of effectiveness against the complete target set.

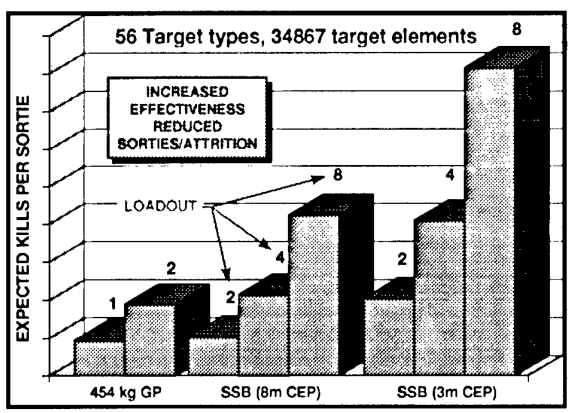


Figure 4. Expected Kills/Sortie for UTA

From Figure 4, we see that to achieve the effectiveness of two 454 kg GP munitions would require a minimum of four SSBs with

an 8-meter CEP accuracy or two SSBs with 3-meter accuracy

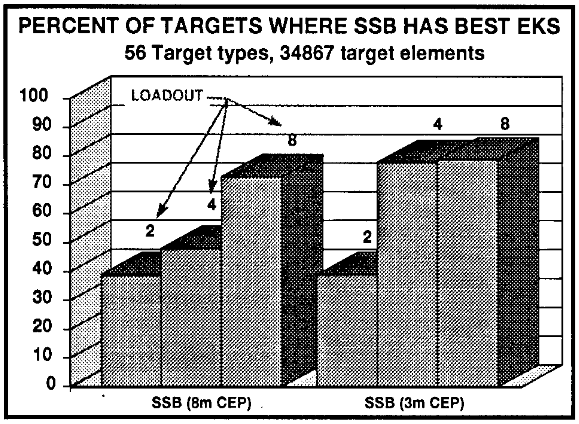


Figure 5. Percent of Target Set Where SSB has the Best EKS

Figure 5 shows the percentage of the 34867 targets where the SSB expected-kill-per-sortie value is higher than the loadout of two 454 kg munitions. We see that a loadout of four SSBs and 8-meter accuracy achieves a best EKS value for slightly less than 50% of the target set. The two 454kg munitions achieve the best EKS for the remaining 50% of the targets. However, a loadout of four SSBs with 3-meter accuracy provides the best effectiveness for almost 80 percent of the targets. By the time a loadout of 8 SSBs is reached, the SSB is the most effective weapon for 75 % of all the targets at either the 8 or 3-meter accuracy. We can make a couple of statements from this observation: 1) There are some targets that are best attacked with 454 kg class munitions, thus a UTA should be able to carry at least a 454 kg class GP bomb, 2) Somewhere between 4 and 8 SSBs with 8-meter accuracy there is a significant number of additional targets where SSB obtains the best EKS. Up to now there has been no indication how much better the EKS value is for the SSB than the 454 kg munition. Figure 6 helps answer this question since the target set is restricted to those targets where the SSB has been shown to have the best EKS. Recall that this restricted set still represents over 75% of the total original set used in this study. For this set of targets we see that even a loadout of two SSBs is as effective as two 454 kg munitions and that four SSBs and 3-meter accuracy provide an average of two targets killed per sortie. When 4 SSBs, which represents 1000-lb (454 kg) in total weight, is compared to a single 454 kg munition of equal weight we can see that on average, the four SSBs (8 meter accuracy) have over 3 times the EKS as the 454 kg weapon. At 3-meter accuracy 4 SSBs have almost 9 times the EKS and has the equivalent weight of a single 454 kg munition.

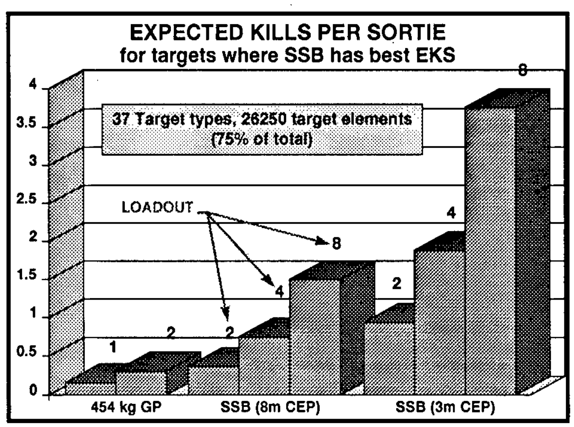


Figure 6. Expected Kills Per Sortie (Targets where SSB has the Best EKS)

This would allow the required number of sorties to be reduced by 300% for an 8-meter SSB and by almost an order of magnitude for a 3-meter accuracy munition. In addition to increasing the conflict tempo, by attacking multiple targets per sortie, a reduction in the total number of sorties required would also reduce attrition, sortie cost, and possibly conflict duration. If these advantages could be realized the additional cost of a terminal seeker to provide a 3-meter accuracy might certainly be justified.

Reviewing figures 4 to 6 with an UTA perspective, a conclusion can be drawn pertinent for the UTA developers. The conclusion is that significant mission flexibility occurs with a minimum payload of 1000 pounds (454 kg). This would allow carriage and deployment of one 1000-lb (454 kg) munitions, two 500-lb (227 kg) munitions, or 4 SSB's. This mix of munitions covers all but the very hardest fixed ground targets. Maximum mission flexibility would occur with a 2000 pound (908 kg) payload capability allowing the loadouts described above to double and provides additional lethal effectiveness.

6.0 CONCLUSIONS

The conclusion of this study is that a small munition concept like the SSB, currently being demonstrated at WL/MN provides excellent effectiveness for all aircraft platforms including an UTA concept. The previous trend for USAF munitions was to increase size, weight, and explosive load, but the corresponding reduction in loadout using a large, heavy munition can reduced the overall effectiveness of each sortie. The high loadouts furnished by the SSB and LOCAAS concepts have increased the sortie effectiveness substantially. Even though multiple SSBs may need to be used against a target, the SSB loadouts possible more than make up for this deficit. Additionally, the increased numbers of munitions "on-target" can provide an increased statistical probability of destroying a critical node of the target over a single large munition. The SSB, in its current configuration, is an effective and viable UTA munition. The small size and weight provides the UTA platform a desirable combat capability for a large number of targets. The study suggests that an UTA with 2000-lb (908 kg) of payload is optimum for a combat capability. With 2000-lb (908 kg) of payload the UTA could carry two 1000-lb (454 kg), 8 SSBs, or 16 LOCAAS. With this flexibility all but the hardest targets are at risk. The soft targets are best defeated with LOCAAS. Large area targets, are most susceptible to large blast/frag, general purpose munitions like the 1000-lb (454 kg). The UTA could carry the 1000-lb (454 kg) munitions side-by-side or 4 SSBs on each side of centerline. The next best payload for the UTA is 1000-lb (454 kg) and results in a single 1000-lb (454 kg), 4 SSBs or 8 LOCAAS. While this is less effective than 2000-lbs (908 kg) of payload, it does allow a smaller UTA design and reduce the propulsion requirements. This payload allows a centerline weapons bay instead of the side-by-side bay mentioned earlier. From figures 4 to 6 it is seen that a drop in UTA payload to 500-lbs (227 kg) only allows two SSBs to be carried with the drastic reduction in effectiveness. With only a 500-lb (227 kg) loadout, more sorties would need to be conducted putting the UTA at risk and increasing cost and conflict duration. *In short, the UTA should maintain a 1000-lb (454 kg) minimum payload if it is to be significantly effective against the target set of interest.*

Not addressed in this study are the aircraft integration and weapon interface issues pertinent to high loadout munitions like the SSB. For current manned aircraft the Mil-Std-1760 capability is required since data must be passed to each munition. In addition to having 1760 capability, the aircraft Operational Flight Profile (OFP) software would need to be developed to correctly initialize, arm, sequence, etc. the multiple munitions. For UTA utilization, similar integration issues are found. While the concept of operations for the SSB would likely provide for loading the GPS target coordinates via mission planning cockpit data cartridge and 1760 interface prior to flight, future real-time targeting would require the capability to pass this information from platform to SSB during flight. The OFP software for an UTA may be even more

complex than for a manned aircraft since a large amount of data that is currently handled by a pilot, may need to be passed from onboard sensors to a manned ground-station support facility. For an UTA combat mission where a target needs to be identified and classified prior to authorizing weapon release, the data may be even more critical especially if the UTA is used in a close-air-support role. Finally, early UTA design criteria should include the requirement for a munition dispenser to maintain the ability to package and release multiple munitions. Dispenser technology is critical to achieve high loadouts in a small volume like an UTA. The dispenser technology must provide the capability to release unitary munitions or multiple munitions on a target to provide the most effective sortie. Most current dispensers that have been demonstrated are dropped as a unit and the dispensing of submunitions occur later. Since the SSBs and LOCAAS need to be dropped as unitary or multiples to achieve the best effectiveness, the dispenser would most likely be a captive dispenser. It would seem prudent to develop dispenser technology that would be adaptable to both manned aircraft and UTA concepts, but this dispenser concept would obviously impact the UTA design and should be integrated early in the design phase.

7.0 REFERENCES

1. Brubaker, D, "A Mission Level Effectiveness Study of a 250-lb Class Air-to-Surface Munition Concept (U)", WL-TR-1997-7002, January 1997

2. "Personal Computer User's Manual for JMEM/AS Open-End Methods", Joint Technical Coordinating Group for Munitions Effectiveness (Air-to-Surface) 61 JTCG/ME-3-16, October 1993

REPORT DOCUMENTATION PAGE

1. Recipient's Reference	2. Originator's Reference	3. Further Reference	4. Security Classification of Document
	AGARD-CP-594	ISBN 92-836-0057-6	UNCLASSIFIED/ UNLIMITED

5. Originator	Advisory Group for Aerospace Research and Development North Atlantic Treaty Organization 7 rue Ancelle, 92200 Neuilly-sur-Seine, France
6. Title	System Design Considerations for Unmanned Tactical Aircraft (UTA)
7. Presented at/sponsored by	Papers presented at the Mission Systems Panel 8th Symposium held in Amfithea (Athens) Greece, 7-9 October 1997.

8. Author(s)/Editor(s)	9. Date
Multiple	July 1998

10. Author's/Editor's Address	11. Pages
Multiple	292

12. Distribution Statement	There are no restrictions on the distribution of this document. Information about the availability of this and other AGARD unclassified publications is given on the back cover.

13. Keywords/Descriptors

UAV (Unmanned Aerial Vehicle)	Tactical aircraft
Design	Operational effectiveness
Reconnaissance	Airborne operations
Navigation	Surveillance
Targeting	Command and control
Guidance	Tactical communications
Tactical intelligence	Detectors
Data fusion	Signal processing
Avionics	

14. Abstract

This volume contains the Technical Evaluation Report, the Keynote Address and the 26 unclassified papers, presented at the Mission Systems Panel 8th Symposium held in Amfithea (Athens) Greece from 7th to 9th October 1997.

The papers presented covered the following headings:

- Applications
- Operational Concepts I & II
- Advances in UTA Techniques and Technologies (NAV, C^3I, G&C)
- Advances in UTA Techniques and Technologies (Sensors, Processing, Data Fusion)

AGARD

NATO OTAN

7 RUE ANCELLE • 92200 NEUILLY-SUR-SEINE

FRANCE

Télécopie 0(1)55.61.22.99 • Télex 610 176

DIFFUSION DES PUBLICATIONS

AGARD NON CLASSIFIEES

L'AGARD détient un stock limité de certaines de ses publications récentes. Celles-ci pourront éventuellement être obtenus sous forme de copie papier. Pour de plus amples renseignements concernant l'achat de ces ouvrages, adressez-vous à l'AGARD par lettre ou par télécopie à l'adresse indiquée ci-dessus. *Veuillez ne pas téléphoner.*

Des exemplaires supplémentaires peuvent parfois être obtenus auprès des centres de diffusion nationaux indiqués ci-dessous. Si vous souhaitez recevoir toutes les publications de l'AGARD, ou simplement celles qui concernent certains Panels, vous pouvez demander d'être inclus sur la liste d'envoi de l'un de ces centres.

Les publications de l'AGARD sont en vente auprès des agences de vente indiquées ci-dessous, sous forme de photocopie ou de microfiche. Certains originaux peuvent également être obtenus auprès de CASI.

CENTRES DE DIFFUSION NATIONAUX

ALLEMAGNE
Fachinformationszentrum Karlsruhe
D-76344 Eggenstein-Leopoldshafen 2

BELGIQUE
Coordonnateur AGARD - VSL
Etat-major de la Force aérienne
Quartier Reine Elisabeth
Rue d'Evere, B-1140 Bruxelles

CANADA
Directeur - Gestion de l'information
(Recherche et développement) - DRDGI 3
Ministère de la Défense nationale
Ottawa, Ontario K1A 0K2

DANEMARK
Danish Defence Research Establishment
Ryvangs Allé 1
P.O. Box 2715
DK-2100 Copenhagen Ø

ESPAGNE
INTA (AGARD Publications)
Carretera de Torrejón a Ajalvir, Pk.4
28850 Torrejón de Ardoz - Madrid

ETATS-UNIS
NASA Center for AeroSpace Information (CASI)
Parkway Center, 7121 Standard Drive
Hanover, MD 21076

FRANCE
O.N.E.R.A. (Direction)
29, Avenue de la Division Leclerc
92322 Châtillon Cedex

GRECE
Hellenic Air Force
Air War College
Scientific and Technical Library
Dekelia Air Force Base
Dekelia, Athens TGA 1010

ISLANDE
Director of Aviation
c/o Flugrad
Reykjavik

ITALIE
Aeronautica Militare
Ufficio Stralcio AGARD
Aeroporto Pratica di Mare
00040 Pomezia (Roma)

LUXEMBOURG
Voir Belgique

NORVEGE
Norwegian Defence Research Establishment
Attn: Biblioteket
P.O. Box 25
N-2007 Kjeller

PAYS-BAS
Netherlands Delegation to AGARD
National Aerospace Laboratory NLR
P.O. Box 90502
1006 BM Amsterdam

PORTUGAL
Estado Maior da Força Aérea
SDFA - Centro de Documentação
Alfragide
P-2720 Amadora

ROYAUME-UNI
Defence Research Information Centre
Kentigern House
65 Brown Street
Glasgow G2 8EX

TURQUIE
Millî Savunma Başkanliği (MSB)
ARGE Dairesi Başkanliği (MSB)
06650 Bakanliklar - Ankara

AGENCES DE VENTE

NASA Center for AeroSpace Information (CASI)
Parkway Center, 7121 Standard Drive
Hanover, MD 21076
Etats-Unis

The British Library Document Supply Division
Boston Spa, Wetherby
West Yorkshire LS23 7BQ
Royaume-Uni

Les demandes de microfiches ou de photocopies de documents AGARD (y compris les demandes faites auprès du CASI) doivent comporter la dénomination AGARD, ainsi que le numéro de série d'AGARD (par exemple AGARD-AG-315). Des informations analogues, telles que le titre et la date de publication sont souhaitables. Veuiller noter qu'il y a lieu de spécifier AGARD-R-nnn et AGARD-AR-nnn lors de la commande des rapports AGARD et des rapports consultatifs AGARD respectivement. Des références bibliographiques complètes ainsi que des résumés des publications AGARD figurent dans les journaux suivants:

Scientific and Technical Aerospace Reports (STAR)
STAR peut être consulté en ligne au localisateur de ressources uniformes (URL) suivant:
http://www.sti.nasa.gov/Pubs/star/Star.html
STAR est édité par CASI dans le cadre du programme NASA d'information scientifique et technique (STI)
STI Program Office, MS 157A
NASA Langley Research Center
Hampton, Virginia 23681-0001
Etats-Unis

Government Reports Announcements & Index (GRA&I)
publié par le National Technical Information Service
Springfield
Virginia 2216
Etats-Unis
(accessible également en mode interactif dans la base de données bibliographiques en ligne du NTIS, et sur CD-ROM)

Imprimé par le Groupe Communication Canada Inc.
(membre de la Corporation St-Joseph)
45, boul. Sacré-Cœur, Hull (Québec), Canada K1A 0S7

AGARD

NATO OTAN

7 RUE ANCELLE • 92200 NEUILLY-SUR-SEINE

FRANCE

Telefax 0(1)55.61.22.99 • Telex 610 176

DISTRIBUTION OF UNCLASSIFIED

AGARD PUBLICATIONS

AGARD holds limited quantities of some of its recent publications, and these may be available for purchase in hard copy form. For more information, write or send a telefax to the address given above. *Please do not telephone.*

Further copies are sometimes available from the National Distribution Centres listed below. If you wish to receive all AGARD publications, or just those relating to one or more specific AGARD Panels, they may be willing to include you (or your organisation) in their distribution.

AGARD publications may be purchased from the Sales Agencies listed below, in photocopy or microfiche form. Original copies of some publications may be available from CASI.

NATIONAL DISTRIBUTION CENTRES

BELGIUM
Coordonnateur AGARD - VSL
Etat-major de la Force aérienne
Quartier Reine Elisabeth
Rue d'Evere, B-1140 Bruxelles

CANADA
Director Research & Development
Information Management - DRDIM 3
Dept of National Defence
Ottawa, Ontario K1A 0K2

DENMARK
Danish Defence Research Establishment
Ryvangs Allé 1
P.O. Box 2715
DK-2100 Copenhagen Ø

FRANCE
O.N.E.R.A. (Direction)
29 Avenue de la Division Leclerc
92322 Châtillon Cedex

GERMANY
Fachinformationszentrum Karlsruhe
D-76344 Eggenstein-Leopoldshafen 2

GREECE
Hellenic Air Force
Air War College
Scientific and Technical Library
Dekelia Air Force Base
Dekelia, Athens TGA 1010

ICELAND
Director of Aviation
c/o Flugrad
Reykjavik

ITALY
Aeronautica Militare
Ufficio Stralcio AGARD
Aeroporto Pratica di Mare
00040 Pomezia (Roma)

LUXEMBOURG
See Belgium

NETHERLANDS
Netherlands Delegation to AGARD
National Aerospace Laboratory, NLR
P.O. Box 90502
1006 BM Amsterdam

NORWAY
Norwegian Defence Research Establishment
Attn: Biblioteket
P.O. Box 25
N-2007 Kjeller

PORTUGAL
Estado Maior da Força Aérea
SDFA - Centro de Documentação
Alfragide
P-2720 Amadora

SPAIN
INTA (AGARD Publications)
Carretera de Torrejón a Ajalvir, Pk.4
28850 Torrejón de Ardoz - Madrid

TURKEY
Millî Savunma Başkanliği (MSB)
ARGE Dairesi Başkanliği (MSB)
06650 Bakanliklar - Ankara

UNITED KINGDOM
Defence Research Information Centre
Kentigern House
65 Brown Street
Glasgow G2 8EX

UNITED STATES
NASA Center for AeroSpace Information (CASI)
Parkway Center, 7121 Standard Drive
Hanover, MD 21076

SALES AGENCIES

NASA Center for AeroSpace Information (CASI)
Parkway Center, 7121 Standard Drive
Hanover, MD 21076
United States

The British Library Document Supply Centre
Boston Spa, Wetherby
West Yorkshire LS23 7BQ
United Kingdom

Requests for microfiches or photocopies of AGARD documents (including requests to CASI) should include the word 'AGARD' and the AGARD serial number (for example AGARD-AG-315). Collateral information such as title and publication date is desirable. Note that AGARD Reports and Advisory Reports should be specified as AGARD-R-nnn and AGARD-AR-nnn, respectively. Full bibliographical references and abstracts of AGARD publications are given in the following journals:

Scientific and Technical Aerospace Reports (STAR)
STAR is available on-line at the following uniform resource locator:
http://www.sti.nasa.gov/Pubs/star/Star.html
STAR is published by CASI for the NASA Scientific and Technical Information (STI) Program
STI Program Office, MS 157A
NASA Langley Research Center
Hampton, Virginia 23681-0001
United States

Government Reports Announcements & Index (GRA&I)
published by the National Technical Information Service
Springfield
Virginia 22161
United States
(also available online in the NTIS Bibliographic Database or on CD-ROM)

Printed by Canada Communication Group Inc.
(A St. Joseph Corporation Company)
45 Sacré-Cœur Blvd., Hull (Québec), Canada K1A 0S7

ISBN 92-836-0057-6